Arnold Schwarzenegger
Governor

COMPRESSED AIR ENERGY STORAGE SCOPING STUDY FOR CALIFORNIA

PIER FINAL PROJECT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Prepared By:
Electric Power Research Institute

November 2008

CEC-500-2008-069

Prepared By:
Electric Power Research Institute
Dr. Robert B. Schainker
Dr. Robert B. Schainker and Abhi Rao
Palo Alto, California 94304
Commission Contract No. 500-01-025
Commission Work Authorization No: WA-14

Prepared For:
Public Interest Energy Research (PIER)
California Energy Commission

Pramod Kulkarni
Contract Manager

Pramod Kulkarni
Program Area Lead
Energy Efficiency RD&D Program

Martha Krebs, Ph.D.
PIER Director

Thom Kelly, Ph.D.
Deputy Director
ENERGY RESEARCH & DEVELOPMENT DIVISION

Melissa Jones
Executive Director

Acknowledgements

The following individuals contributed critical comments and material to Energy Power Research Institute that was incorporated into this report:

- Dr. Michael Nakhamkin, Energy Storage Power Corporation
- Mr. Noah Matthews, PB Energy Storage Systems

Please cite this report as follows:

Schainker, Robert B., Abhi Rao 2008. *Compressed Air Storage (CAES) Scoping for California, USA.* California Energy Commission, PIER Energy-Related Environmental Research Program. CEC-500-2008-069.

Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The PIER Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Compressed Air Storage (CAES) Scoping Study for California is the final report for the Energy Power Research Institute E21 Master Agreement project (contract number 500-01-025) conducted by Energy Power Research Institute. The information from this project contributes to Grid Stability and Integration of Renewables.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-654-4878.

Table of Contents

List of Figures

List of Tables

Abstract

This report presents the results of a technical scoping study on the compressed air energy storage technology. Compressed air storage may potentially meet the California Energy Commission's goal to "reduce the cost of electricity and increase value" by enabling a relatively new energy storage option be technically evaluated for potential use in California. The compressed air energy storage technology allows less expensive nighttime electricity energy to be effectively stored such as wind or other off peak generation, replacing relatively more expensive, peaking daytime energy. Since compressed air energy storage plants have quick time response and excellent part-load characteristics and can provide ramping power (up or down) as needed by the California Independent System Operator (California ISO).

The report documents the following project results:

1. Identifies potential geologic sites/regions in California that can be used by compressed air energy storage plants to cost-effectively store off-peak and/or renewable energy.
2. Identifies and analyzes potential compressed air energy storage preliminary designs that could use the below-ground compressed air energy storage geologic sites in California.
3. Identifies and analyzes potential compressed air energy storage preliminary designs that use above-ground air piping or air vessel systems for the air storage system.
4. Presents California maps showing natural gas transmission systems and high-voltage transmission systems to cost-effectively implement compressed air energy storage plants in California.
5. Recommends future compressed air energy storage research and development to meet California needs.

Keywords: CAES, compressed air energy storage, electricity storage, depleted gas/oil fields, salt caverns, above-ground storage options, CAES plant design, adiabatic-compressed air energy storage, siting CAES, siting compressed air energy storage, CAES opportunities in California, energy storage for wind energy

Executive Summary

New energy storage technology uses off-peak electricity to compress air into an underground reservoir, surface vessel, or a piping air storage system. When electricity is needed, the air is withdrawn, heated via combustion with fuel, and passed through an expansion turbine to drive an electric generator. These plants burn about one-third the premium fuel of a conventional combustion turbine and produce about one-third the pollutants per kilowatt-hour generated. In another option, no fuel is used to heat the air before it is passed through the expansion turbine, using instead air that is heated with stored energy from the waste heat produced during the off-peak compression process and/or heated from the exhaust of a combustion turbine (which is part of the compressed air energy storage plant). The compressed air can be stored in several types of underground, including porous rock formations, depleted gas or oil fields, and salt or rock cavern formations. The compressed air can also be stored in above-ground or near-surface pressurized air vessels/pipelines, including those used to transport high-pressure natural gas.

Since December 1978, a 290 megawatt (MW), four-hour compressed air energy storage plant has been in operation in Huntorf, West Germany and has demonstrated a strong performance of 90 percent availability and 99 percent starting reliability. This plant uses two mined salt caverns to store the air.

Over the last 20 years, the Electric Power Research Institute sponsored numerous technical and economic studies to determine the technical feasibility and economic viability for developing compressed air energy storage plants in the United States. These studies found that about three-fourths of the United States has geologic resources potentially suited for siting compressed air energy storage plants. The required turbines and compressors are available off-the-shelf from a number of vendors, and can provide modular plants in sizes ranging from 10 MW to 400 MW. As a result, the compressed air energy storage technology is a viable energy storage option in the United States, with the first United States-based plant going on-line in June 1991, and built by Alabama Electric Cooperative, with Energy Power Research Institute's assistance, at a site located near the town of McIntosh, Alabama (about 44 miles north of Mobile, Alabama). This plant has a capacity of 110 MW, and its underground reservoir is sized to produce this electricity output for a maximum continuous time of 26 hours. The underground air storage medium for this facility is a mined salt cavern of about 19.6 million cubic feet, operating between about 1280 pounds per square inch from a full charge to 680 pounds per square inch from a full discharge of the air store. The Alabama Electric Cooperative plant was built based on a competitively awarded fixed-price, turnkey contract, costing about $460 per kilowatt (1991 dollars). The plant was built in about 2.5 years. The one major design difference between the German and Alabama compressed air energy storage plants— is the Alabama plant had an exhaust gas heat exchanger in it to heat the air after it came from storage, which reduced the plant's fuel use by 25 percent.

In the last 10 years numerous advanced compressed air energy storage cycles have been developed and evaluated by Energy Power Research Institute. Some require less fuel than the "conventional" designs used at the German and Alabama plants. Most take advantage of the developments in simple-cycle and combined-cycle gas turbines plants however some advanced compressed air energy storage plant designs use the "waste" heat from the compression cycle to minimize (or reduce to zero) the fuel-based heat needed during the expansion-generation cycle of the plant.

California's policy is to increase renewable energy and develop ways that allow these electricity sources to more effectively follow the daily demand increase and decrease residential and industrial consumers. Compressed air energy storage could be cost-effective addition to California's generation mix to meet such consumer needs. This report documents a compressed air energy storage study focused on two broad areas—the identification of potential compressed air energy storage sites in California and the latest modular compressed air energy storage design approaches that could be implemented in California, using either below-ground or above-ground air storage systems.

Compressed Air Energy Storage Underground Air Storage Location Opportunities

The underground geologic formations suitable for compressed air energy storage in California are numerous since there are many gas and oil fields in the state. Over time, many of these sites are now "depleted" and could serve as reliable compressed air energy storage sites. "High-level" map shows current California sites used to store natural gas (Figure E-1). The detailed geologic characteristics of most of these sites are available from state records and have proven to be stable with excellent gas pressure "tightness" and are attractive for potential compressed air energy storage use.

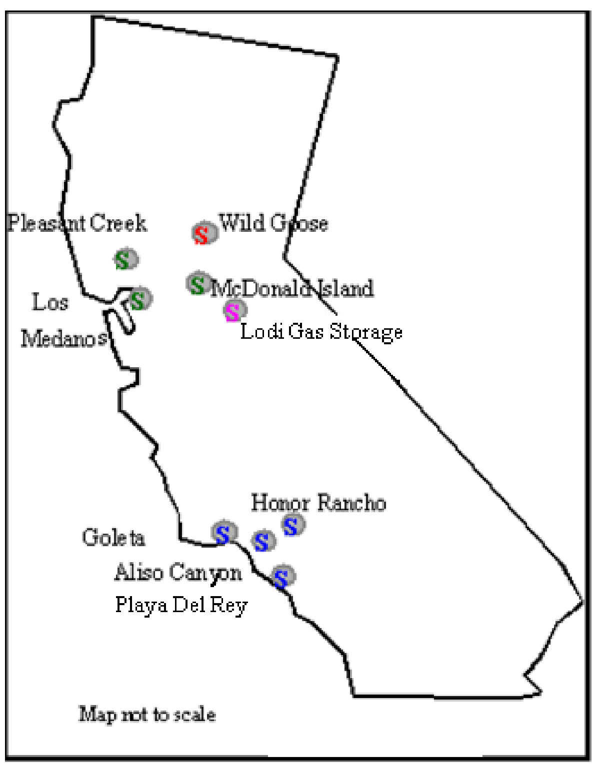


Figure E-1: Depleted Gas Field Sites Used to Store Natural Gas in California

Compressed Air Energy Storage Above-Ground Air Storage Opportunities

Above-ground air storage vessels or air storage pipeline systems can also be used to store compressed air. There are a number of organizations "reinventing" this option each having its own specialized design. Such systems are very attractive because they allow CAES plants to be sited almost anywhere, since no underground geologic formation is needed. However, such systems are estimated to be about five times more expensive than underground salt-based air storage caverns and about 50 times more expensive than porous rock-based air storage systems. Future research and development on these above ground air storage systems is a good topic for future research and should reduce their cost.

Compressed Air Energy Storage Plant Design Options Suitable for California

A summary is presented (Table E-1) for performance and costs of various compressed air energy storage plant design options. Each design relies on a different approach to pressurize the air using commercially available turbomachinery. It should be emphasized that these data were generated based on previous experience and without specific site-specific optimizations dictated by local economics, electricity loads and costs, geological formations, equipment, and installation costs. This data must be investigated further with the aim of lowing capital and/or operational costs of a compressed air energy storage plant at a specific site.

Table E-1: Summary of Performance and Cost Estimates for Various Second Generation Compressed Air Energy Storage (CAES) Plant Design Options and a Simple-Cycle Combustion Turbine[1]

	CAES – Conventional	CAES - Air Injection	CAES - AI & HP Expander	CAES - AI & HP and LP Expander	CAES - Expander	CAES - Expander & Inlet Chilling	CAES- Adiabatic	Simple Cycle CT (GE 7FA (at 95F)
Total Power, MW	110	193	202	433	400	427	72	160
Off-Peak Comp. Power, MW	81	29	30	318	288	300	96	NA
Relative Cavern Volume	1.0	1.08	0.85	1.4	1.35	1.35	1.5	NA
Total Power Fuel Related HR, Btu's/kWh	3967	8394	8182	3819	3696	3809	0	10,600
Energy Ratio KWh-in/ kWh-out	0.80	0.85	0.69	0.73	0.69	0.70	1.3	NA
Approximate Specific Capital Cost, $/kW	727	327	403	506	507	482	1000	500

Source: Electric Power Research Institute

Note: HP = High Pressure and LP = Low Pressure

The analysis of the data in Table E-1concludes the following:

- There are a variety of compressed air energy storage plant design options that should provide significant benefits to California including economically attractive energy storage and power regulating capacity for wind resources or other renewable projects in California.
- The conventional compressed air energy storage plant design option, such as the Alabama compressed air energy storage plant, has a relatively high capital cost compared to the newer compressed air energy storage plant design options.

1. The combustion turbine used to produce the data in Columns 3 through 8 in Table E-1 is a GE Frame 7A. The costs above are only to be viewed on a relative basis and not on an "absolute" cost basis. The CAES costs are for a 10-hour underground salt based air storage system, or for a 2-hour above ground air storage system. The costs are in 2007 dollars and do not include interest during construction, final engineering, permitting, or substation costs.

- A variation of the conventional compressed air energy storage plant design is called the adiabatic compressed air energy storage plant design. This storage option has an advantage since it does not require burning of any fuels during power generation. It uses off-peak energy (from renewable energy or other energy resources) for air compression and storage, and as a heat source during compressed air energy storage power generation cycle. This design option has a capital cost of about $1000 per kilowatt and has a number of components that require research and development, optimization, and overall plant component integration and controls.
- The other compressed air energy storage plant design options (generally can be called a compressed air energy storage-combustion turbine plant) have the following features:
    - Simplicity
    - Reduction in capital costs by about 30 percent to 50 percent
    - Fuel cost reductions
    - Flexibility to meet power requirements, from 10 to 400 megawatts:
        - Obtained by using any one of a number of commercial available combustion turbines, including the commonly used GE 7241 combustion turbine (that is, a GE Frame 7A combustion turbine).
        - Obtained by properly sizing other plant equipment.
    - The compressed air energy storage-combustion turbine plant design approach can easily be applied to numerous old/used existing combustion turbines with similar cost effectiveness.
    - The compressed air energy storage-combustion turbine design option has a short construction or on-line installation schedule since it uses standard equipment without any new or untried components (for example, it does not use a new high-pressure combustor) or a complicated configuration (such as an integrated multi-compressor, multi-expander turbomachinery train on "one shaft" like the Alabama plant).
    - The new compressed air energy storage - combustion turbine design option using a 10 megawatt class combustion turbine, (with only a small increase in dollars per kilowatt capital costs) is attractive when combined with above-ground air storage systems. Such a compressed air energy storage plant with a two- to three-hour above-ground air storage system would likely be at least one-half the cost of a battery storage plant.
- A compressed air energy storage plant could be developed using an underground geological formation or a manmade air storage cavern. As demonstrated at the Alabama facility, the cost of an air storage plant created by solution mining a salt deposit is not impacted by the number of storage hours produced by the compressed air energy

storage plant and why the Alabama air storage system can support a 26-hour discharge level at its full plant rating of 110 megawatts. Compressed air energy storage with an above ground air storage system, due to its relatively high cost for air storage vessels/pipelines, is much more applicable for plants with a shorter discharge level (for example, two to three hours) and small megawatt capacity (for example, 10 to 20 megawatts).

Suggested Research, Development, and Demonstration Projects

The most important research and development associated with compressed air energy storage in California should focus on performing cyclic field tests on underground air storage formations including at least two types of attractive underground reservoirs such as depleted gas and oil fields. First, core samples should be investigated regarding any impacts from geochemistry associated with storing air in these formations using standard autoclave evaluations of the samples taken from the depleted gas/oil sites. The core samples could be obtained from the local State Geologic Survey or, if necessary, by drilling into the underground formation with a small bore drilling rig to obtain "clean" core samples.

Analysis, development, and final engineering of new compressed air energy storage plants (using the compressed air energy storage –combustion turbine design options or the adiabatic compressed air energy storage plant design option) must focus on using commercially available equipment to enhance the plant's reliability and to reduce the plant's capital cost. However, in California, even with commercial plant components, there are still numerous research and development efforts required to ensure safe and cost-effective plant operation, especially where compressed air energy storage plants must be properly integrated into renewable (for example, wind) generation. For example, compressed air energy storage plant control systems must specifically be developed to follow the loads and power fluctuations associated with the California grid.

Most, if not all, of the research and development issues associated with new compressed air energy storage plants in California could be effectively addressed by demonstration projects, with well thought-out test procedures to apply the demonstration project results to a variety of compressed air energy storage plant design options, differentiated by size and equipment module additions.

These demonstration projects could use existing old or used small capacity combustion turbines to reduce the capital costs of the projects. For example, a demonstration project could integrate various compressed air energy storage plant design configurations with an above-ground storage system with about two to three hours of storage capacity. Special hybrid equipment additions/retrofits to the demonstration plant could then address and evaluate the real-world performance of various compressed air energy storage plant design alternatives, including the adiabatic plant design alternative.

The most recent and economically attractive compressed air energy storage plant design option uses a combustion turbine as a central component in the plant. A demonstration project could be based on an existing combustion turbine from a California utility willing to contribute the used equipment. Also, the amount of air in the exhaust stream of this combustion turbine used in the demonstration project can be much smaller than all the exhaust air available, since the demonstration project must only provide proof of principle data to evaluate the thermodynamics and performance characteristics of the plant design. For example, five megawatts is all that is required if it uses only a portion of the exhaust air for heating the stored air; or, the demonstration plant could use all the exhaust air from the combustion turbine and produce hundreds of megawatts of output power, depending on the combustion turbine size from the contributing utility.

These research and development suggestions and others are summarized in recommended priority order:

- Work with California utilities to identify potential compressed air energy storage sites within their regions and verify underground geologic conditions applicable to compressed air energy storage (for example, perform core sample chemical analyses, and porosity, permeability and storage pressure and capacity investigations).
- Use a new or used combustion turbine from a California host utility to build and test compressed air energy storage - combustion turbine demonstration plant. Depending on the amount of air flow directed from the combustion turbine exhaust, the compressed air energy storage - combustion turbine plant could produce five to 100 megawatts of plant output.
- Perform thermodynamic trade-off studies to choose preferred compressed air energy storage - combustion turbine plant design and determine the plant parameters appropriate to California geologic site conditions and California off-peak/on-peak renewable energy economic conditions.
- Perform air storage cyclic field tests at one or more California compressed air energy storage sites and test compressed air energy storage - combustion turbine combustor performance, using different air residence times in the storage reservoir, which will determine if chemical reactions in the air store process could affect the plant's performance.
- Design and build a prototype above-ground air store system, and perform field tests to determine corrosion or cyclic fatigue issues.
- Develop a preferred no-fuel compressed air energy storage plant design (that is, the adiabatic compressed air energy storage plant design option) and perform lab/field tests to determine the preferred thermal store materials that are best suited for California conditions.
- Analyze compressed air energy storage plant design options based on alternative fuels (for example, biofuels and hydrogen).
- Analyze adding a synchronous condenser feature to appropriate compressed air energy storage-combustion turbine plant design options, since reactive power injection maybe

needed in California as more wind plants are put into service (for example, “excite” the compressor motor, the combustion turbine generator, and the expander generator to enable them to be used as synchronous condensers).

Benefits to California

Electricity energy storage in general, and bulk storage assets such as compressed air energy storage in particular, provide the California electricity system an operating flexibility that has only been available till recently through pumped hydro system. Since the large-scale hydro electric storage sites are few due to geographic, environmental, and time constraints, compressed air energy storage is an attractive option.

Electricity energy storage provides California’s electric system operational flexibility and imparts other valuable benefits to the changing electricity generation resource mix. Increased use of renewable energy in California, such as the utility scale wind electricity systems, are intermittent and this intermittency can be managed more effectively allowing load shaping of wind resources using bulk electricity storage.

Finally, the California electric system is facing sharp demand peaks. Additional bulk storage such as compressed air energy storage will help reduce the system wide peak, help meet the remaining demand with clean energy sources such as wind, and reduce the use of conventional peaking turbines.

1.0 Introduction

The objectives of this project are to identify practical and cost effective compressed air energy storage (CAES) plant design options useful to optimize and control operations of renewable energy resources in California. Specifically, this project will identify and analyze a number of CAES plant design options that are expected to meet a variety of California requirements. The analysis will include overall plant practicality, cost, performance and plant flexibility related to plant MW capacity and energy storage magnitude, and technical risks for a variety of underground as well as above ground compressed air stores.

Also, this project will identify potential research and development (R&D) projects that are needed for safe and practical deployment of CAES plants in California.

First generation CAES plant technology has been well proven via the successful operating history of two existing CAES plants, one in Huntorf, Germany, and one in McIntosh, Alabama. The Huntorf plant is a 290 MW plant (owned by the RWE German utility). It was designed and built to provide spinning reserve duty and started operation in December, 1978. The McIntosh plant is a 110 MW plant (owned by Alabama Electric Cooperative). It was designed and built to provide peak-shaving / load management duty and started operation in June, 1991. The McIntosh plant incorporates a recuperator (an air to air heat exchanger) to recover exhaust heat from the plant in order to preheat air from the air storage cavern. This resulted in a greatly improved heat rate (by 25%) for the Alabama plant as compared to the Huntorf plant. During the many years of successful operation of these two plants, the CAES technology has demonstrated the technical viability for load management; peak shaving, spinning reserve, load following, regulation, and peaking and intermediate duty applications.

1.1. Organization of Report

After this Introduction, the report begins with geologic opportunities for CAES in California, focusing on depleted gas and oil formations to store the compressed air. Chapter 3 then presents a discussion of using above ground vessels or pressurized air pipeline systems to store the air for CAES use, and Chapter 4 presents a detailed discussion of numerous CAES plant thermodynamic design options suitable to the renewable power ramping and frequency control challenges in California. Chapter 5 then presents a discussion and maps for natural gas pipeline systems, high voltage transmission systems and detailed gas pipeline systems for Pacific Gas and Electric Company, Southern California Gas and San Diego Gas & Electric Company. The cost effective implementation of CAES in California will depend on finding sites where the geologic siting opportunities "intersect" the gas and electric infrastructures in California shown by these maps. The report then concludes with a discussion of possible R&D topics the Energy Commission should consider to support, to further the development and deployment of CAES plants for California.

2.0 Geologic Opportunities in California for CAES Plants That Use Underground Air Storage Reservoirs

California is a large state with abundant natural resources. Underground geologic CAES air storage sites are plentiful and can be used to enhance the utilization of California's wind and other renewable resources. California's underground geologic formations are conducive to storing air (and natural gas and carbon dioxide) because of the flexible and varying geographic nature of the California's underground sedimentary layers. Large concentrations of hydrocarbons have been retained in several of these geologic basins for millions of years. The nature of the sedimentary layers allows them to be used for a wide variety of gas and liquid storage systems. Even so, one of California's drawbacks for underground storage systems can be attributed to numerous earthquake faulting zones. Earthquakes pose a leak risk to underground storage; however, virtually all of California's gas and liquid storage sites are located away from the areas that are vulnerable to earthquake faulting, or the sites are at depths that are not impacted by the faulting. California's geological attributes have the capacity to store 70 million tones of gas every year; each ton can be stored for approximately 40 dollars. In California's central valley, the sand layers have been measured in intervals from 800m to 3300m. In many areas, these geologic basins are found with a thickness of more than 1200 meters, which is ideal for air, natural gas, oil or other fluid storage.

2.1. Depleted Natural Gas Fields in California Provide CAES Siting Opportunities

Depleted natural gas fields gained popularity in the late 1940s and early 1950s. In many situations, it was uneconomical to construct storage tanks for natural gas; consequently, storing compressed gas underground became common and is now a commercially viable industry in California. The geological characteristics of permeability and porosity help determine the economic practicality of using a depleted gas site for CAES application. Permeability refers to the rate at which the natural gas can flow through the formation; whereas, porosity relates to the amount of gas the formation can hold. In any depleted formation, approximately one half of the gas injected must remain as a cushion for the natural gas that will be stored and extracted on a seasonal basis. In storage sites, where previous gas has been stored, this cushion already exists and is usually compromised of natural gas and/or other hydrocarbon compounds. Based on the CAES scoping study performed for this project, over 128 gas field sites were identified that have over 1.8 Gega Ton (Gt) of storing capacity and over 120 oil field sites were identified that have over 3.4Gt of storage capacity. Also, there are over 415 depleted storage sites in California, which are owned by 114 different natural gas operators. On average, these facilities have a storage capacity of about 3,900 Billion cubic feet and have a daily deliver ability rate of about 78 Billion cubic feet a day. As of February 7th, 2007 almost 3,200 Billion cubic feet of natural gas has been stored successfully in California. The largest gas field in California is the Rio Vista Gas field. This underground storage reservoir is lined with sedimentary layers of sand and shale, which is common in California and provides an excellent cap rock to safely store any type of gas.

2.2. Porous Rock Formations in California Provide Siting Opportunities of CAES

Porous rock formations (also called porous rock media or aquifer media) are both porous and permeable. An example would be a naturally occurring porous rock deposit filled with saline water in layers of sandstone. Salt water filled aquifers are ideal in locations where there are no depleted gas fields and when underground salt rock or hard rock formations are not available. A porous rock saline aquifer site that is developed for natural gas storage takes a number of years to developed, since the in-situ saline water requires more cushion gas than a depleted natural gas field site. Thus, siting opportunities for CAES using saline porous rock formations require more development efforts than those at depleted gas field sites. To identify and measure the CAES storage potential using a porous rock saline aquifer for CAES application, one can use the same methods that oil and gas companies use to store natural gas in such sites. When evaluating a saline aquifer site, one must keep in mind various considerations, which include the thickness of the sand/limestone and the caprock's ability not to leak.

2.3. Hard Rock Formations in California Offer Siting Opportunities for CAES

California is characterized by having quaternary sedimentary rock under the central, interior territory. This rock is made up of gravel, silt, clay or sand. The coastal areas are covered in Mesozoic granite and sedimentary rock. The granite was formed from liquid hot magma; whereas, the Mesozoic sedimentary rock is composed usually of sandstone and shale. The most abundant type of layer is the extensive shale sealer. Abandoned coal mines are another possible storage medium. There are deep and untapped coal deposits, which are inaccessible to use. These coal seams can be used to store any gas. According to a screening survey, there is a heavy presence of porous and permeable sediments distributed through California. One site is believed to be able to hold over 300 metric tons (Mt) of gas. California's central valley is also believed to be able to store 500Mt of gas.

EPRI hired a geologic service company PB-ESS that is a leading engineer and constructor of underground storage and related surface facilities. The firm's mission is to provide a full range of quality services in the highly specialized field of subsurface systems technology with particular emphasis on underground hydrocarbon storage (gas or liquid) and related facilities. [Note: PB-ESS is a wholly owned by Parsons Brinckerhoff (PB), a century-old firm ranked among the Engineering News – Record's top 50 US engineering firms]. PB-ESS conducted a review of the literature applicable to this CAES project and interviewed company personnel and individuals in the natural gas storage industry that are active in developing storage in California. The result of this work shows that there are several oil and gas fields (reservoirs) in California that should be seriously considered for CAES application. In addition, the PB-ESS research finds that there is a high level of interest in the CAES subject, and there are some projects now being planned to be developed in California.

PB-ESS research found several sources of information in the energy industry literature related to the evaluation, selection and development of CAES. The most complete source of information related to this project for finding a listing and maps of the oil and gas fields in California, was the 2005, California Division of Oil, Gas and Geothermal Resources (DOGGR) publication of active and abandoned *Oil and Gas Field Production and Reserves.*

To expedite the work for this CAES study, PB-ESS utilized the information found in this publication as a basis for this scoping study project. Thus, the maps presented herein show the locations in California of oil and gas fields where CAES plants using such underground reservoirs could be excellent CAES sites.

During the course of this CAES study, PB-ESS had the opportunity to make a cursory survey of other work related to the general subject of CAES and the particular search for CAES sites in California. These other studies cover CAES in all geologic formations usually used for gas storage; reservoirs, salt caverns, hard rock mined caverns and porous rock aquifers. This additional information (reports and papers) is listed in the Appendix D.

2.4. Geologic Structures for Underground Gas Storage

Compressed gas can be stored in several types of underground structures, with four types usually considered for gas storage (hydrocarbon gases or compressed air):

- Oil and Gas Reservoirs
- Porous Rock Aquifers
- Salt Caverns
- Mined Caverns (Solution mined or machinery/man mined)

There is current activity in CAES around the world, including IPP projects in the Southeast US, Israel Electric Company, the Far East and Germany. Most of these projects utilize salt caverns for CAES. However, aquifer based porous media sites are plentiful in California (and in many other parts of the US) and offer less expensive siting opportunities than salt formations (that do not seem to be available in California, based on the limited scoping study performed and described herein). Thus, presented below is a review of potential CAES siting opportunities based on a scoping review of the California oil and gas fields that could be used to site CAES plants.

2.5. California Oil and Gas Reservoirs

The geology of the oil and gas fields (onshore), in general, follows the Great Central Valley through California. Most of the *gas fields* are located East and Northeast of San Francisco within the Sacramento Basin between Modesto and Red Bluff. Most of the *oil fields* are to the Southeast of San Francisco within the San Joaquin Basin in Kern County and South of Los Angeles to Long Beach.

Maps of the oil and gas fields are included with this study to show the location of the active and abandoned gas fields in California. Three maps are included in the Appendix B to this report. The map shown in Figure B.1 shows all the oil and gas fields in California; and the maps shown in Figure B.2 and Figure B.3 show the location of the oil and gas fields in detail. There are three Township and Range coordinate systems on the DOGGR 2001 maps; The Humboldt Meridian and Base Line (NW, Geothermal District 3), The Mount Diablo Meridian and Base Line (Central and North, Geothermal

District 1) and The San Bernardino Meridian and Base Line (SE, Geothermal District 2). Most of the natural gas fields are in Central and North Central California and utilize the Mount Diablo coordinate system to locate a specific field.

There are more than 400 separate oil and gas production fields (active and abandoned) and nearly 1,000 reservoirs listed by the California Division of Oil, Gas and Geothermal Resources. The oil and gas fields in California produce oil, oil and gas, and dry gas. The size (gas reserves or storage capacity) of the fields vary from a few thousand barrels of oil and/or a small volume (in millions of cubic feet) of gas, to fields with millions of barrels of oil and several billion cubic feet (BCF) of gas. Many of these gas fields (small and large) could be suitable for compressed air storage, depending on the design and size of the CAES power generating facility.

EPRI hired PB-ESS to compile a list of all the oil and gas fields listed by DOGGR. PB-ESS has also compiled a "first cut" list of those fields in California that could be considered viable for CAES. However, because of the potentially high development costs and operating expenses of large storage fields, and the potential safety issues of using oil fields for air storage, this list is limited to the *active, dry gas fields* with approximately 25 billion cubic feet (or less) of estimated production (i.e., storage capacity). The abandoned gas fields should also be considered as a possibility for compressed air storage. However, reactivation and conversion of the abandoned gas fields for compressed air storage would incur some additional capital investment. The list of fields complied by PB-ESS will utilize the Mount Diablo coordinate system to locate the fields. A complete list of all the oil and gas fields in California is cataloged in the 2005 DOGGR publication (Reference 1).

There are numerous gas fields in California that can be considered for CAES application. Most of the gas fields to be considered are located in central or north-central California. Most of the oil fields are located in south-central and southwest California. A few of these oil fields may be candidates for CAES projects. More detail evaluation of these fields is needed to select the preferred oil or gas field sites for CAES.

Table 2.1: Selected Oil and Gas Fields to Be Considered for CAES (by PB-ESS for EPRI)

Field Name (District Number) Reservoir Name	Township / Range Mount Diablo Base Line and Meridian	Cumulative Gas Produced (MMcf)
Afton Gas (6)	1W-19N	
Main Area		19,188
Angel Slough Gas (6)	1W-18N	
Kione		400
Forbes		133
Ash Slough Gas (5)	14E-10S	
Blewett		6,103
Belgian Anticline (4)	21E-30S	
Miocene		1,116
Eocene		17,050
Butte Sink Gas (6)	1W-16N	7,525

Butte Slough Gas (6)	1W-16N	9,528
Cache Creek Gas (6)	2E-10N	
Starkey		1,782
Winters		1,240
Chowchilla Gas (5)	14E-10S	
Zilch Upper Sands		2,334
Garzas		256
Cretaceous		25,137
Clarksburg Gas (6)	4E-7N	
Pollock		5,420
Corning, South Gas (6)	3W-24N	4,617
Davis Southwest Gas (6)	2E-8N	2,844
Dixon, East Gas (6)	1E-7N	751
East Islands Gas (6)	6E-3N	
Mokelumne River		3,698
Gill Ranch Gas (5)	17E-13S	
Upper Cretaceous		7,439
1st Panoche		14,501
Grand Island Gas (6)	4E-5N	5,837

Field Name (District Number) Reservoir Name	Township / Range Mount Diablo Base Line and Meridian	Cumulative Gas Produced (MMcf)
Greenwood Gas (6)	3W-22N	
Eocene		240
Forbes		1,918
Greenwood, East Gas (6)	3W-21N	
Forbes		3,208
Grizzly Bluff Gas (6)		
Rio Dell		570
Howells Point Gas (6)	1E-12N	2,031
Karnak Gas (6)	3E-11N	
Starkey		3,488
King Island Gas (6)	5E-3N	
Mokelumne River		10,446
Kirby Hill Gas(6)	1W-4N	
Domengine		13,979
Little Butte Creek Gas (6)	1E-19N	213

Lone Star Gas (6)	2W-15N	
Forbes		3,457
Medora Lake Gas (6)		
Winters		2,749
Merrill Avenue, Southwest Gas (5)	13E-11S	
Blewett		8,057
Merritt Gas (6)	2E-9N	4,084
Mint Hill Gas (5)	13E-10S	
Blewett		2,032
Moffat Ranch Gas (5)	15E-12S	
Kreyenhagan		9,659
Cretaceous		1,894
Orland Gas (6)	2W-22N	1,004

Field Name (District Number) Reservoir Name	Township / Range Mount Diablo Base Line and Meridian	Cumulative Gas Produced (MMcf)
Pierce Road Gas (6)	2E-14N	
Forbes		9,685
Guinda		1,101
Putah Sink Gas (6)	3E-8N	
Starkey		5,803
Rancho Capay Gas (6)	2W-22N	11,315
Sugarfield Gas (6)		
Starkey		2,240
Winters		1,080
Sycamore Slough Gas (6)	1W-12N	
Forbes		873
West Butte Gas (6)	1E-16N	
Forbes		2,979
Williams Gas (6)	2W-16N	
Forbes		1,310
Willow Slough Gas (6)	2E-9N	
Starkey		4,427
Winters		3,616
Woodland Gas (6)	1E-10N	

Source: Electric Power Research Institute

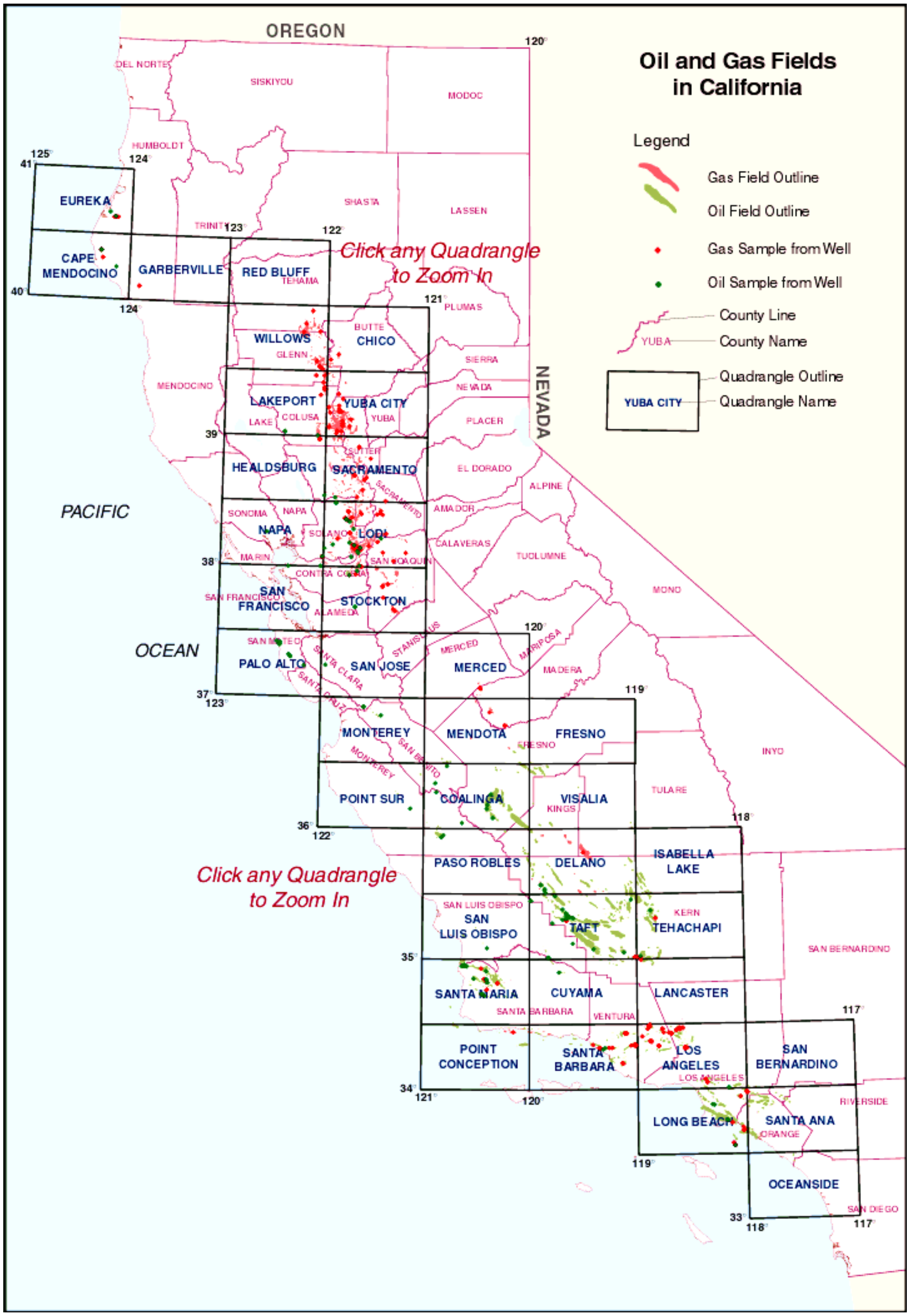


Figure 2.1: Oil and Gas Fields in California Where CAES Sites Can Be Investigated

Source: Electric Power Research Institute

PG&E Investigated This Site in the 1990's for CAES

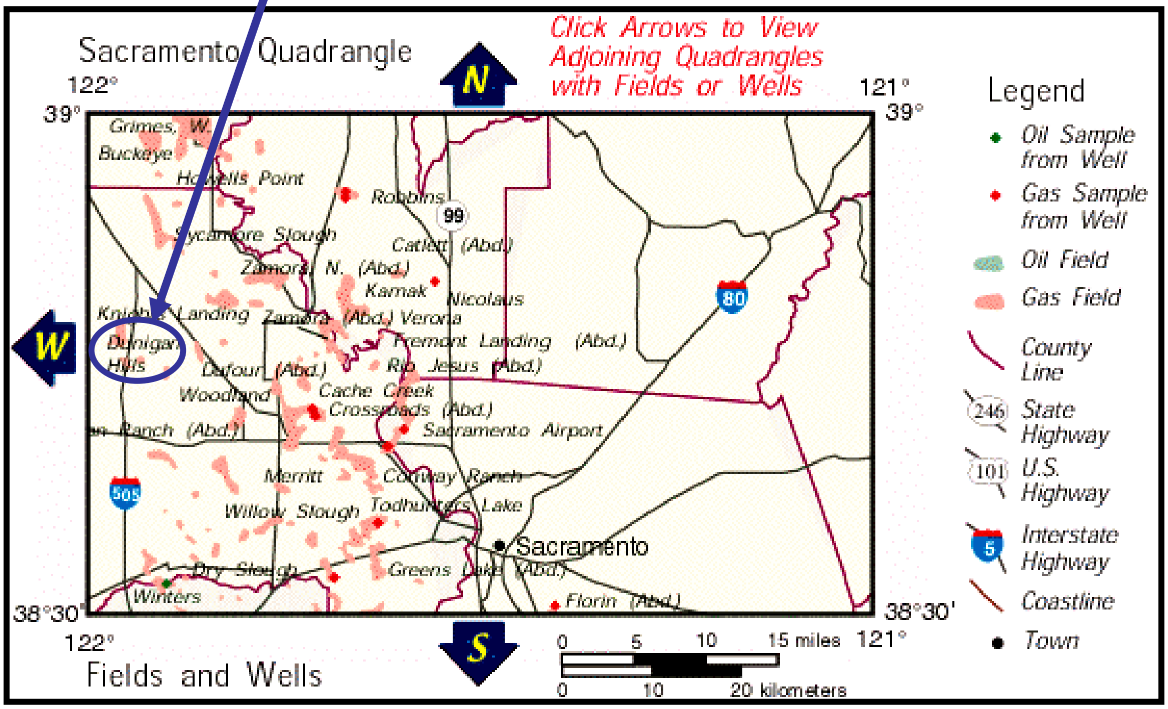


Figure 2.2: Detailed Map of Potential CAES Sites Near Sacramento
Source: Electric Power Research Institute

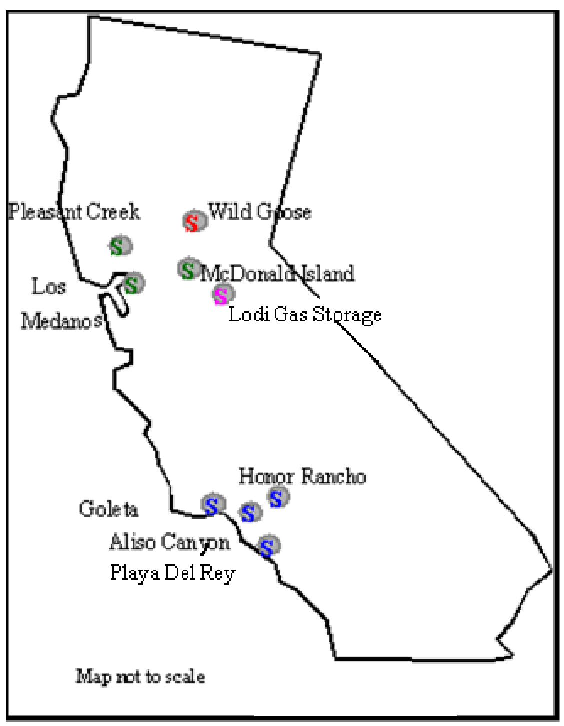


Figure 2.3: California Gas Storage Sites
Source: Electric Power Research Institute

3.0 Above-Ground Air Vessels and/or Air Pipeline Systems Used to Store Air for CAES Plants

Above-ground storage systems can also be used to store air for CAES plants. Electric Power Research Institute and others have investigated alternative ways to store the air in such a manner as to reduce the costs to reasonable levels. At present, the cost to store 10 hours of pressured air underground is about the same cost as it is to store about 2 hours of pressured air above ground. Thus, for wind or PV applications that do not need more than about two hours of storage, such systems should be investigated further. One such system is shown below and uses a high pressure gas pipeline system (see Figure 3.1). Another type of air storage system uses air vessels to store the compressed air (see Figure 3.2).

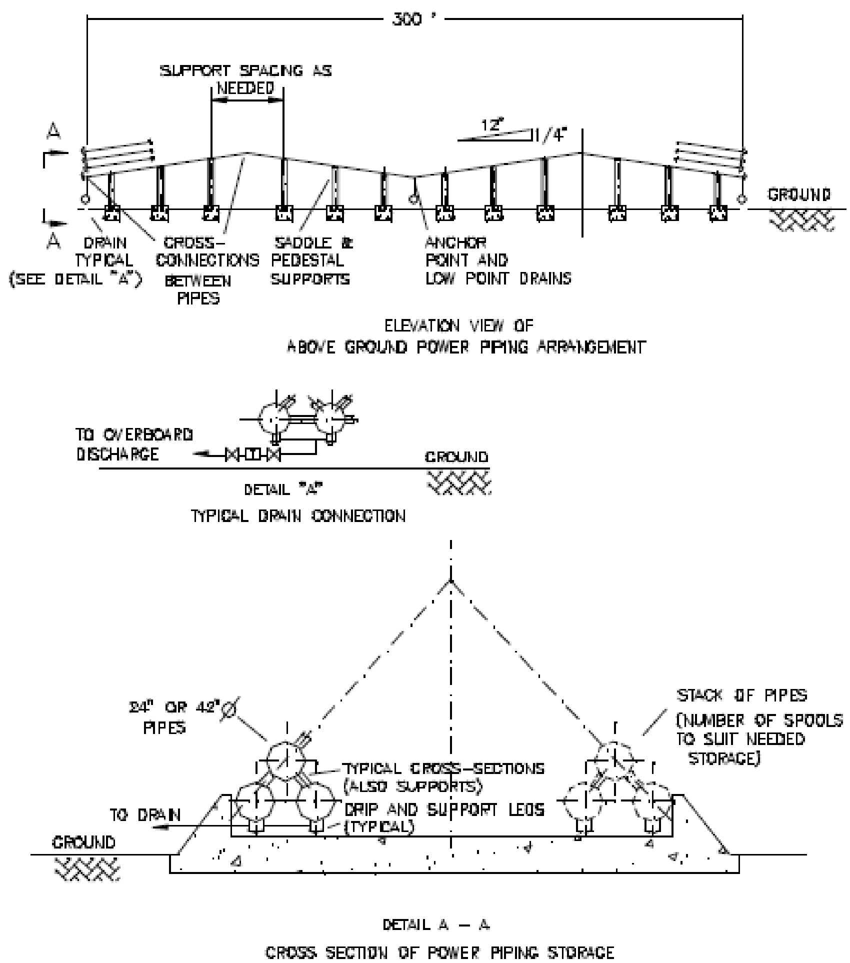


Figure 3.1: Cross Sections of Above-Ground Pressurized CAES Air Storage Systems
Source: Electric Power Research Institute

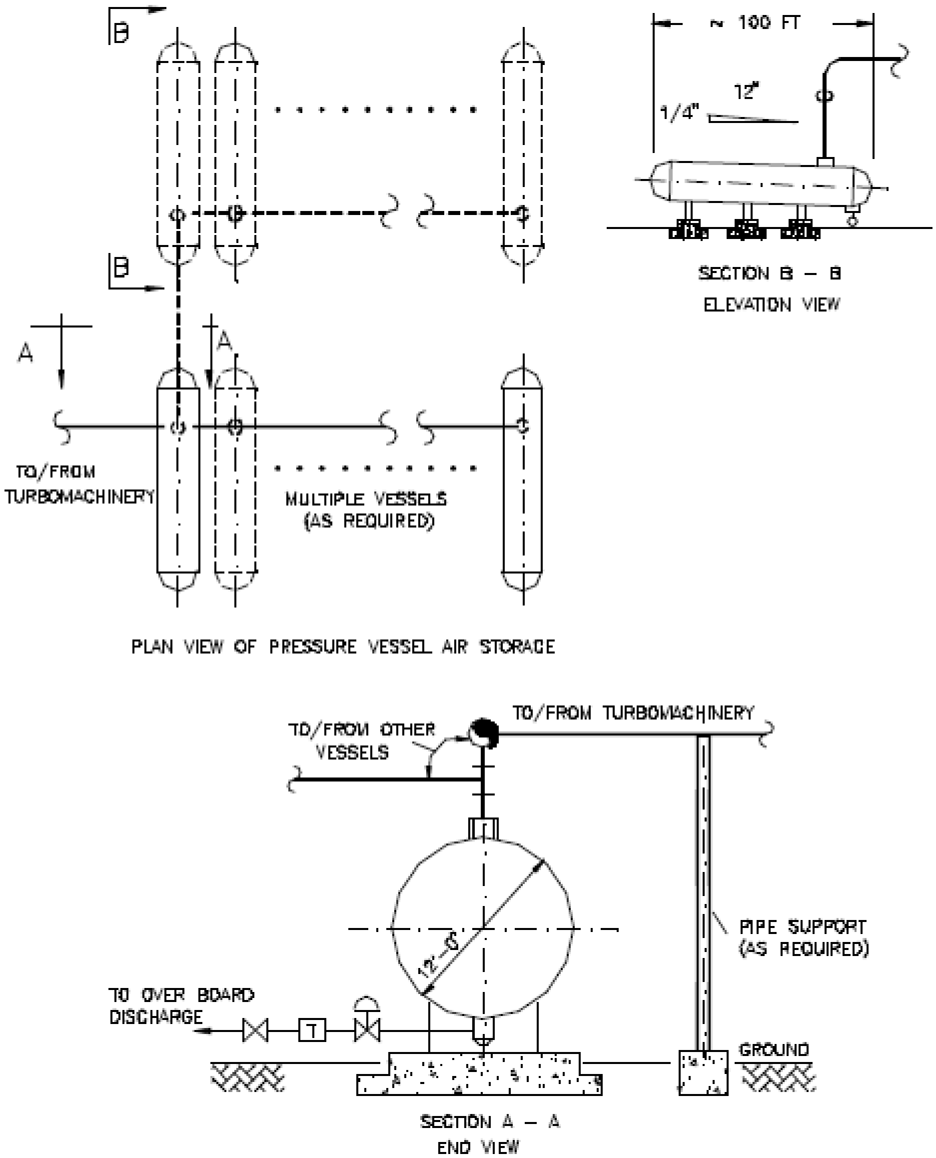


Figure 3.2: Plan-View and End-View Sections of Above-Ground Pressurized CAES Air Storage Systems
Source: Electric Power Research Institute

The above ground air storage systems are attractive for CAES plants since no underground geologic formations are needed to store the pressurized air, which allows the plant builder/owners to site such plants almost anywhere. However, the cost for such systems are about a factor of 5 more expensive than an underground salt cavern based CAES plant; and, such above ground systems are about a factor of 50 more expensive than porous rock based air storage systems. More R&D however in this area should reduce the cost of such above ground air storage systems. Even so, such above ground systems are very likely much less expensive than two hour battery plants.

4.0 CAES Plant Turbomachinery Options Suitable to California Conditions

The approach used to investigate and present alternative CAES plant designs applicable in California is to first present for the reader the capital and performance characteristics of the Alabama Electric Cooperative (AEC) CAES plant (see Table 4.1) as a reference plant, and then present some specific alternative CAES plant design options suitable for California and compare these new CAES plant designs to the AEC plant, in terms of capital cost and operating performance parameters.

Table 4.1: Reference Plant Specifications: From The Alabama Electric Cooperative (AEC) McIntosh CAES Plant

AEC McIntosh CAES Power Plant	
Plant Power Capacity (MW)	110
Storage Hours	26
Hours of Compression per Hour of Generation	1.6
Storage Geology	Salt
Storage Volume (million cubic feet)	19.6
Fuel	Gas
Compression Air Flow (lb/sec)	208
Expansion Air Flow (lb/sec)	340
Recuperator Cold Side Air In/Out Temp (F)	95/546
Recuperator Hot Side Gas In/Out Temp (F)	696/293
HP Expander Inlet Temperature (F)	1000
HP Expander inlet Pressure (psia)	620
LP Expander Inlet Temperature (F)	1600
LP Expander Inlet Pressure (psia)	218
Power Production Heat Rate (Btu/kWhr)	4100
Plant Charging Ratio (kWhr-In/kWhr-Out)	0.81

Source: Electric Power Research Institute

Today, two turbomachinery vendors offer equipment similar to that used in the AEC CAES plant; namely, Dresser Rand (module size = 135 MW) and Alstom (module size = 400 MW). Both vendors have put together a preferred CAES plant design that is rigid not only in the specified plant size but also in allowable operating air flows and pressures, which affect the air store depth and volume. These conditions may be met in California but make it difficult to adjust the plant specifications to meet the needs of specific renewable plant capacities, modes of plant operation, and underground geologic formations in California. Figure 4.1 displays the configuration, power and thermodynamic parameters of the conventional, reference case AEC CAES plant design option.

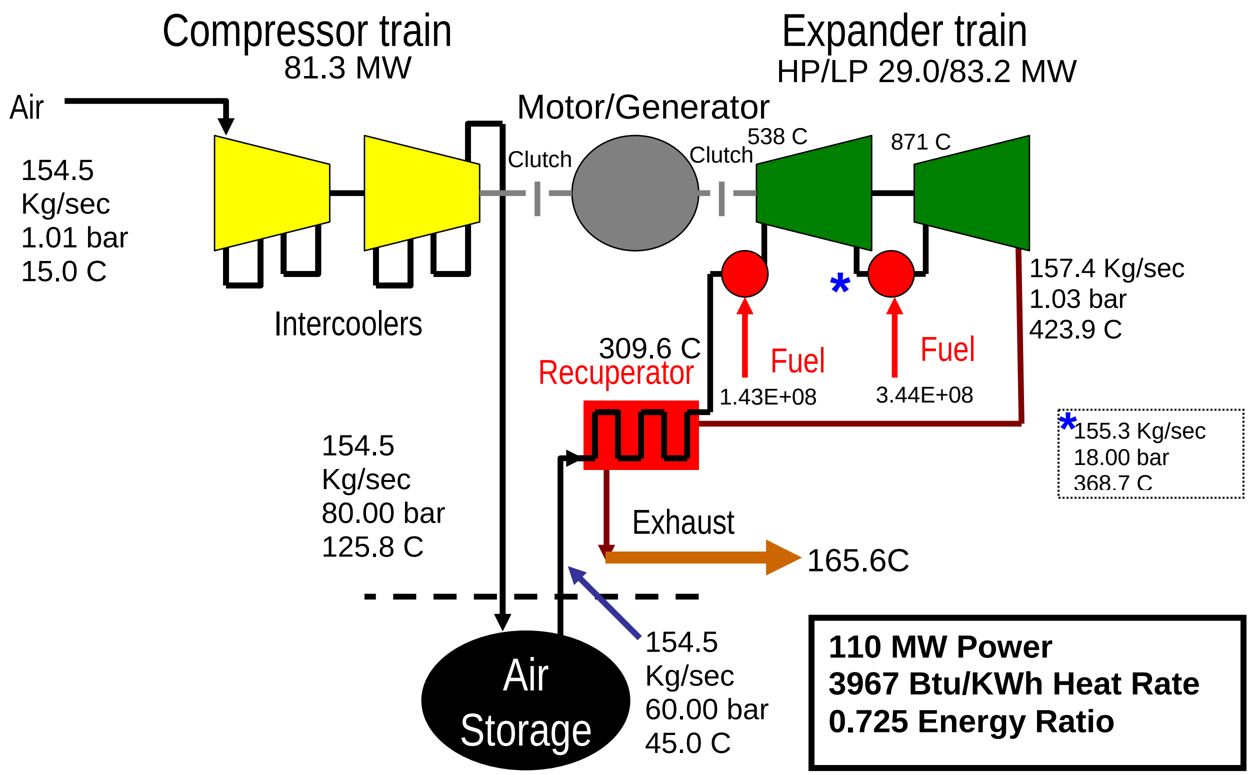


Figure 4.1: Conventional CAES Plant Schematic (i.e., the AEC McIntosh Plant)
Source: Electric Power Research Institute

4.1. CAES Plant Design Options Based on Standard Combustion Turbine Power Blocks

There is a strong interrelationship between a CAES plant design, the plant equipment specifications, vendor equipment chosen and the storage geology for each site being investigated. For example, the choice of the minimum inlet pressure to the expander determines the minimum storage pressure, sets the required air compressor discharge pressure, and impacts the efficiency of the overall CAES plant operating cycle. Also, the allowable storage pressures and the storage cost are dependent upon the storage geology. Thus, the CAES plant design, plant concept and equipment specifications all must be "optimized" simultaneously with the economic and operating constraints imposed by the company attempting to build a CAES plant. In response to these needs and challenges, presented below are CAES plant design options that are able to provide a variety and flexibility for CAES plant capacities and energy storage pressures. Using these design options will allow the user to improve the overall CAES plant performance and operating modes while reducing both the plant's capital costs and operating costs. These plant design options utilize existing technology by incorporating off-the-shelf gas turbines, compressors, and expanders into the overall plant design.[2]

The new CAES plant design options enable the CAES technology to have lower capital costs, shorter delivery times, and higher operational flexibility than those for the conventional AEC CAES plant design. The new CAES plant design options utilize a standard combustion turbine (CT) engine as the only equipment which consumes fuel. The CT exhaust heat provides the heat energy input to the compressed air that is withdrawn from the storage system and expanded through a CAES expander in order to generate the CAES plant power output. There is no need for development and use of customized high pressure (HP) and low pressure (LP) combustors, which were a challenge during the AEC CAES project. The gas turbine vendors and equipment could be properly selected to optimize the CAES plant size and the operational performance of the plant, which would be chosen to best meet the specific needs of the California grid (e.g., the MW size of the compressor and expander, the maximum storage hours for the plant, and the regulating rates, efficiency, and ramping characteristics of the overall plant.

A summary is presented below of the results of the CAES plant design options investigated in this project:

- The CAES-Air Injection (CAES-AI) design option is based on the injection of the stored and preheated air into a CT, thus providing an increase in the CT power output, due to the way the stored air is used. The CAES-AI design option is relatively simple and is expected to have the lowest specific CAES plant capital costs; particularly if it is based on an already existing operating CT at a California utility. This design option is applicable to a variety of new or existing combustion turbines.
- The CAES-AI/HP expander design option is the CAES-AI concept with an HP expander utilizing preheated stored compressed air based on the high pressure difference between the stored air pressure and the pressure required for injection into CT. As compared to CAES-AI concept, this concept has higher CAES power output.
- The CAES-AI/Expander design option is the CAES-AI/HP design option with the following differences:
    - o The expander operates between the stored air pressure and atmospheric pressure, with the extraction for air injected into CT.
    - o The expander inlet compressed air flow is a subject for optimization and not limited by the injection flow into the CT.

2. The new CAES plant designs use a simple cycle combustion turbine module as a central element in the overall CAES plant design. These designs are patented by Energy Storage and Power Corporation, which is willing to license any of these designs to any utility or Independent Power Producer in the State of California, if the CEC/EPRI financially supports the demonstration or construction of any of these CAES design options in California. (Note: The above statement documents a communication between EPRI's Robert B. Schainker and the President of ESPC, Mike Nakhamkin, on March 23, 2007).

The CAES power for this concept is the CT power increase plus the expander power, both generated by the stored air.

- The CAES/Expander/Inlet Chilling design option is similar to CAES-AI/Expander design with the following differences:
  - o The expander is fed by the stored air preheated in the heat exchanger without an extraction of air injected into CT.
  - o The expander is optimized to have its exhaust flow equal to the CT inlet flow, with an exhaust "chilled" temperature of about 10C to 15C (50F to 59F).
  - o The expander exhaust is injected into the CT inlet.

  The CAES power for this design option is the expander power plus the CT power increase, due to the inlet temperature being lower than ambient temperature during on-peak time periods when the plant would be generating power.

- The CAES - Bottoming Cycle design option is based on an expander that is being fed by the stored compressed air preheated in the exhaust heat exchanger.

The above novel CAES plant design options utilize a standard, off-the-shelf CT, compressor, expander, motor, and heat exchanger. These components are offered by several vendors, and can be delivered as a packaged unit. It is envisioned that several smaller compressors could be used instead of a single large compressor, which would improve the plants reliability and allow for variations in storage-mode compressor power consumption during off-peak hours (e.g., from available but fluctuating wind turbine power during off-peak time periods).

The expanders in the CAES plant design options discussed earlier have relatively low inlet temperatures (below 538C/1000F), which allows for the use of existing standard expanders or back pressure steam turbine expander equipment to be used in the CAES plant. This will yield a reduced overall plant capital cost and reduced complexity for the overall CAES plant.

As cited in the discussions above, and to conduct a fair comparative analysis of the various CAES plant design options investigated, it is assumed herein that all the CAES plant design options will operate with the underground storage geology used in AEC's 110 MW CAES plant (i.e., a solution mined salt cavern). Thus, the following air storage parameters are used in the comparative analysis that will be presented later:

- The storage geological formation is a salt dome
- The depth of the storage is 1500 ft (approximately 460m)
- The minimum storage pressure is approximately 40 bars (i.e., 580 psia)
- The maximum storage pressure is approximately 90 bars (i.e., 1305 psia)
- The storage volume for each concept was estimated on the relative basis based on the specific air consumption per kWh of peaking energy produced, and the associated costs

were estimated based on the AEC's cavern cost being proportioned by the storage volume and airshaft diameter.

- The ratio of the compression hours to generation hours is equal to two. This means that compressors have been sized for half of the CAES plant expander air flows.
- The volume and costs for the above ground air storage option for each design investigated is similarly estimated based on the relative specific air consumption per kWh of peaking energy produced and specific costs estimated.

Of course, once the geologic parameters of a given California site are available, and the compression versus generation hours ratio is determined, based on California load shape characteristics, the comparative analysis described herein needs to be updated to be sure the best CAES plant design option is chosen.

4.2. Performance Estimates of CAES Plant Options Based on Standard Combustion Turbine Power Blocks

This section presents performance characteristics of the CAES plant options based on a standard CT power block. Heat and mass balance estimates were developed using the GE-GATE Cycle modeling software. In order to produce performance estimates for each CAES plant design option, the CT used to do the calculations was a GE7241-FA combustion turbine, which is a common CT used by electric utilities today.

The section below provides specific performance characteristics for each considered CAES plant design option. The overall section concludes with a comparative analysis of the performance characteristics of all the considered CAES plant design options.

4.2.1. CAES-AI Concept

The schematic for the CAES-AI plant design option and its major performance characteristics are presented on Figure 4.2a. Performance characteristics of the GE7241-FA CT at the same ambient conditions are presented on the Figure 4.1b. The difference between the CAES-AI design power of 193MW (Figure 4.2a) and the CT power of approximately 160MW (Figure 4.2b) represents the CAES power of 33 MW generated by the stored air injected into CT. The table below summarizes the major performance characteristics of CAES-AI and the CT.

	CAES-AI Plant Option Based on GE7241-FA CT	**GE7241-FA CT (at 95F)**
CT power, MW	160	160
CAES power, MW	33.3	NA
Total power, MW	193.1	160
Total heat rate, Btu/kWh	8394	10,600
Off-peak compressor power, MW	29.1	NA

The CAES-AI plant design option has the following major plant components:

- existing or new combustion turbine,
- compressed air storage system
- multiple compressors, as appropriate, for compressed air energy storage charging during off-peak hours, utilizing renewable sources whenever possible
- Heat recovery recuperator (HRR)
- Balance of Plant (BOP) equipment

The stored compressed air is preheated in the HRR, utilizing the exhaust gas heat, and then is injected into an existing/new CT (at a pressure consistent with the combustion turbine compressor discharge pressure) for CT power augmentation for the CAES power generation cycle.

The key advantages of the CAES-AI plant design option is its simplicity and it has the lowest specific capital costs ($/kW), particularly if an existing CT is used.

Because utility peak load requirements are most often met by a CT, operation of CTs and CAES plants would practically coincide. The total power of a CAES-AI plant consists of the CT power generated with the CT's heat rate and the incremental CAES power generated with approximately a 4000 Btu/kWh heat rate. The CAES power for this concept is 33.3 MW.

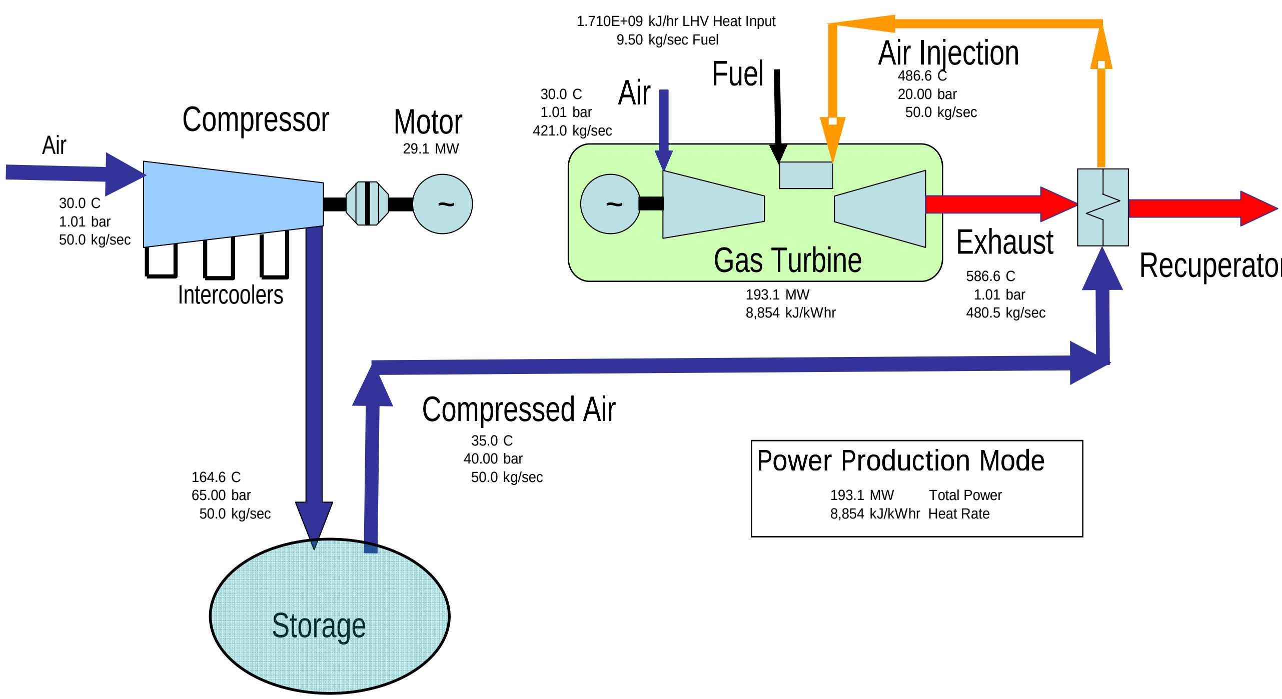


Figure 4.2a: Schematic and Heat and Mass Balance for the CAES-AI Plant Option
Source: Electric Power Research Institute

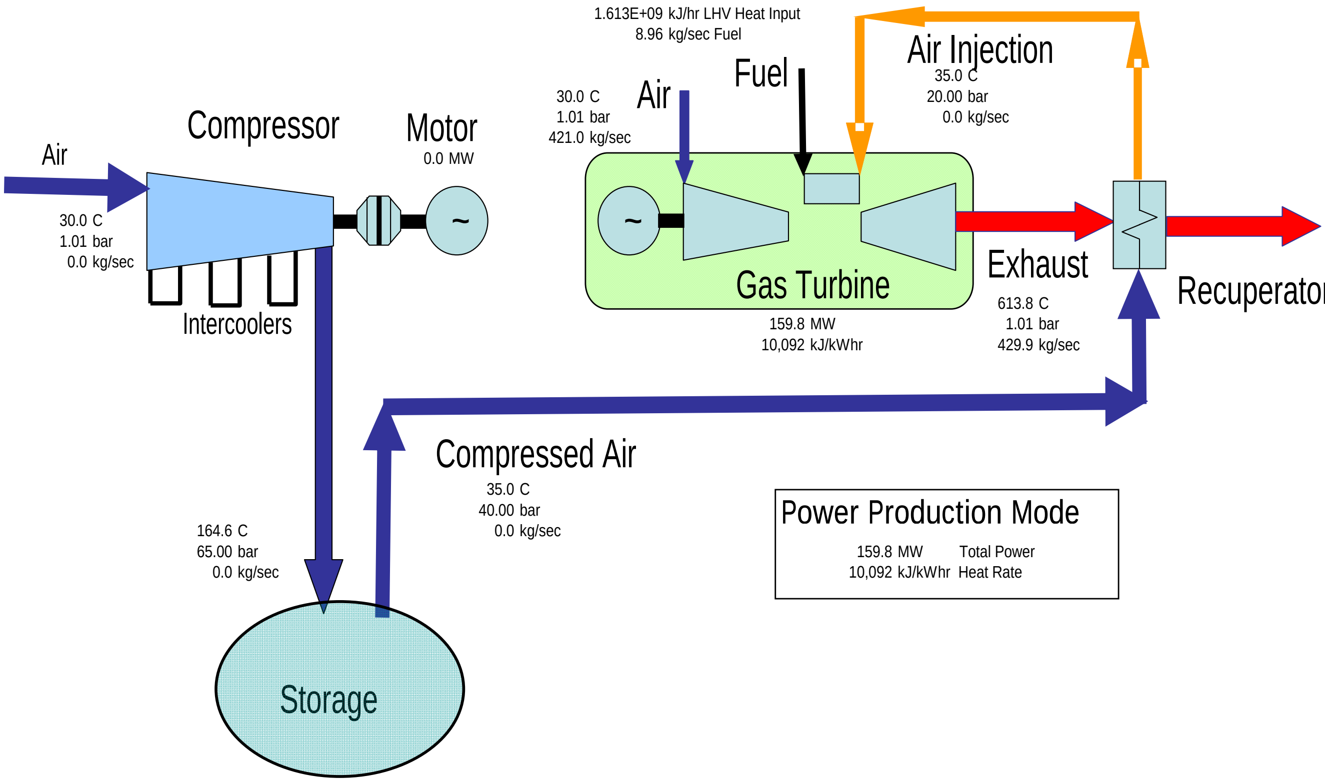


Figure 4.2b: Schematic and Heat and Mass Balance for the CAES-AI Plant Option Without Air Injection (Based on Performance of GE7241-FA CT)
Source: Electric Power Research Institute

4.2.2. CAES-AI/HP Expander Concept

The schematic of the CAES-AI/HP Expander plant design option and its major performance characteristics are presented on Figure 4.3. The CAES-AI/HP Expander design has the same components as the CAES-AI plant option plus the high pressure expander sized for the maximum injection flow allowable by the CT. The stored compressed air is preheated in the HRR, utilizing the exhaust gas heat, and then is directed into the HP expander utilizing preheated stored compressed air with the pressure differences between a relatively high stored air pressure and the pressure required for air injection into the CT.

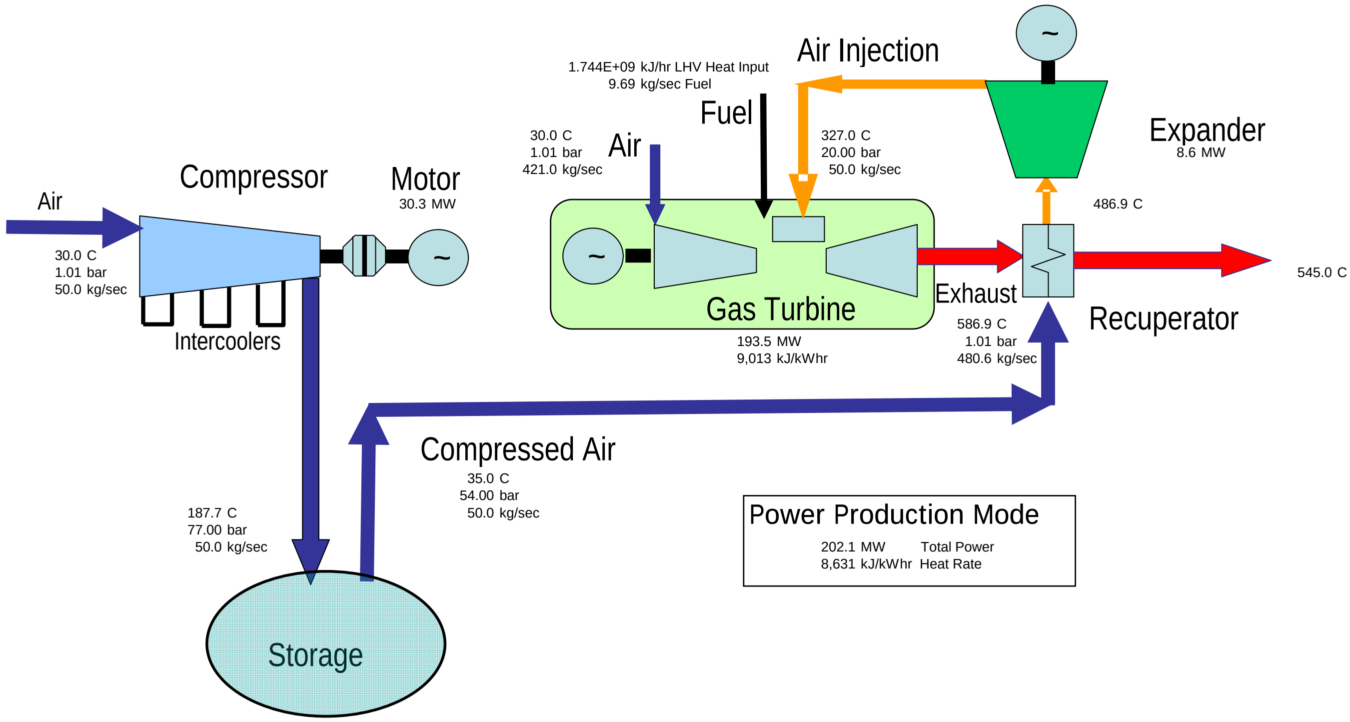


Figure 4.3: Schematic and Heat and Mass Balance for the CAES-AI/HP Expander Plant Option
Source: Electric Power Research Institute

The table below summarizes the major performance characteristics of CAES-AI/HP Expander design and the Combustion Turbine.

	CAES-AI/HP Expander Plant Option Based on GE7241-FA CT	GE7241-FA CT (at 95F)
CT power, MW	159.8	160
CAES power, MW	42.3	NA
Total power, MW	202.1	160
Total heat rate, Btu/kWh	8181	10600
Off-peak compressor power, MW	30.3	NA

4.2.3. CAES-AI/ Expander Concept

The schematic of the CAES-AI/Expander concept with its major performance characteristics are presented on Figure 4.4. The CAES-AI/HP Expander has the same components as the CAES-AI/HP Expander concept with the following differences:

- The expander operates between the stored compressed air and atmospheric pressures
- The expander has an extraction of air with parameters consistent with the air injection into the CT

- The expander inlet compressed air flow is a subject for optimization and not limited by the injection flow into the CT.

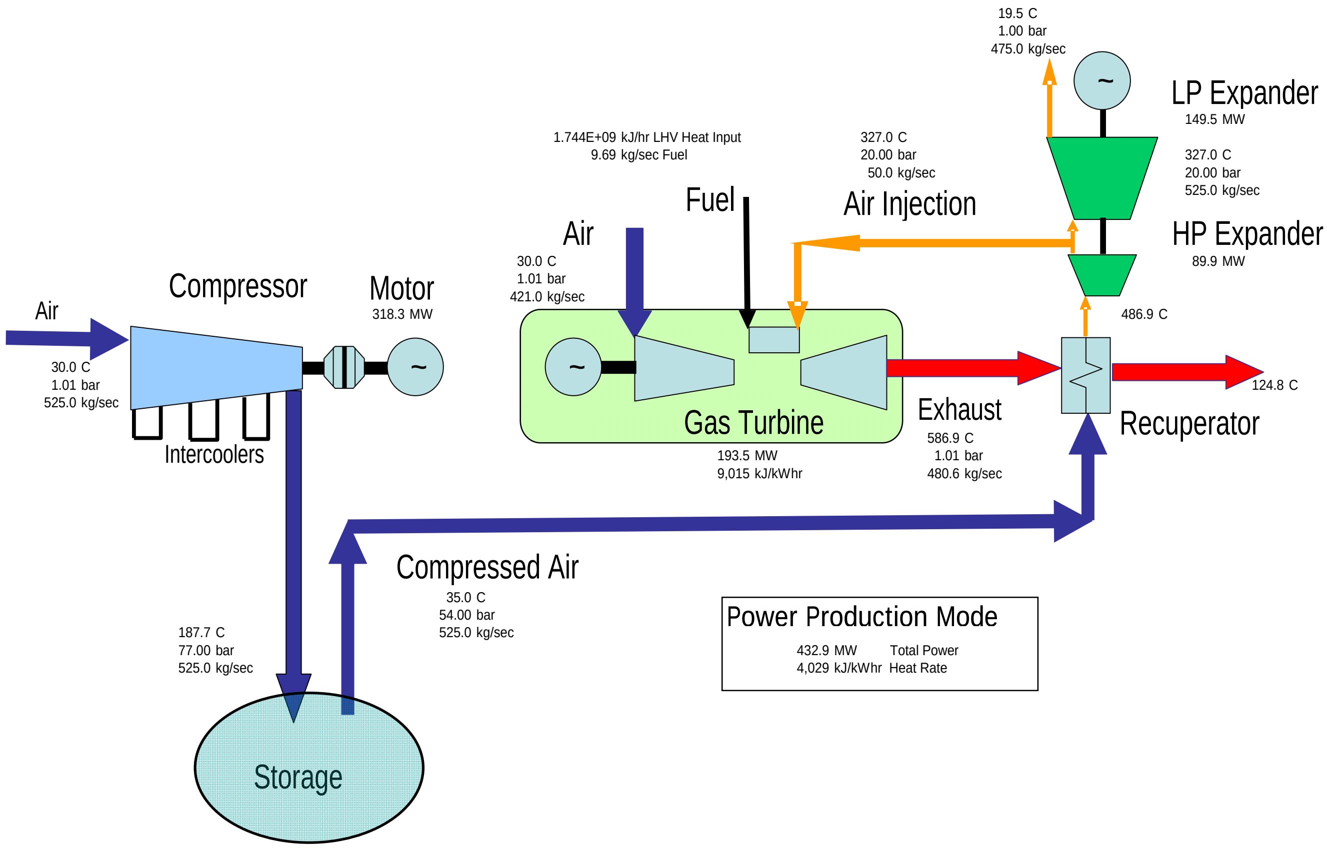


Figure 4.4: Schematic and Heat and Mass Balance for the CAES-AI/Expander Concept
Source: Electric Power Research Institute

The table below summarizes major performance characteristics of CAES-AI/Expander vs. Combustion Turbine.

	CAES-AI/Expander Plant Option Based on GE7241-FA CT	**GE7241-FA CT (at 95F)**
CT power, MW	159.8	160
CAES power, MW	273.1	NA
Total power, MW	432.9	160
Total heat rate, Btu/kWh	3819	10600
Off-peak compressor power, MW	318.3	NA

4.2.4. CAES/Expander/Inlet Chilling Plant Design Option

The schematic of the CAES-AI/Expander/Inlet Chilling design with its major performance characteristics are presented on Figure 4.5. The CAES-AI/HP Expander has the same components as the CAES-AI/Expander concept with the following differences:

- The expander has no extraction for air injection into the CT
- The expander is optimized to have the exhaust flow equal to the CT inlet flow and the exhaust temperature of approximately 10C to 15C (50F to 59F)
- The expander exhaust is injected into the CT inlet

The CAES power for this design is the expander power plus the CT power increase, due to its inlet temperature being lower than ambient temperature.

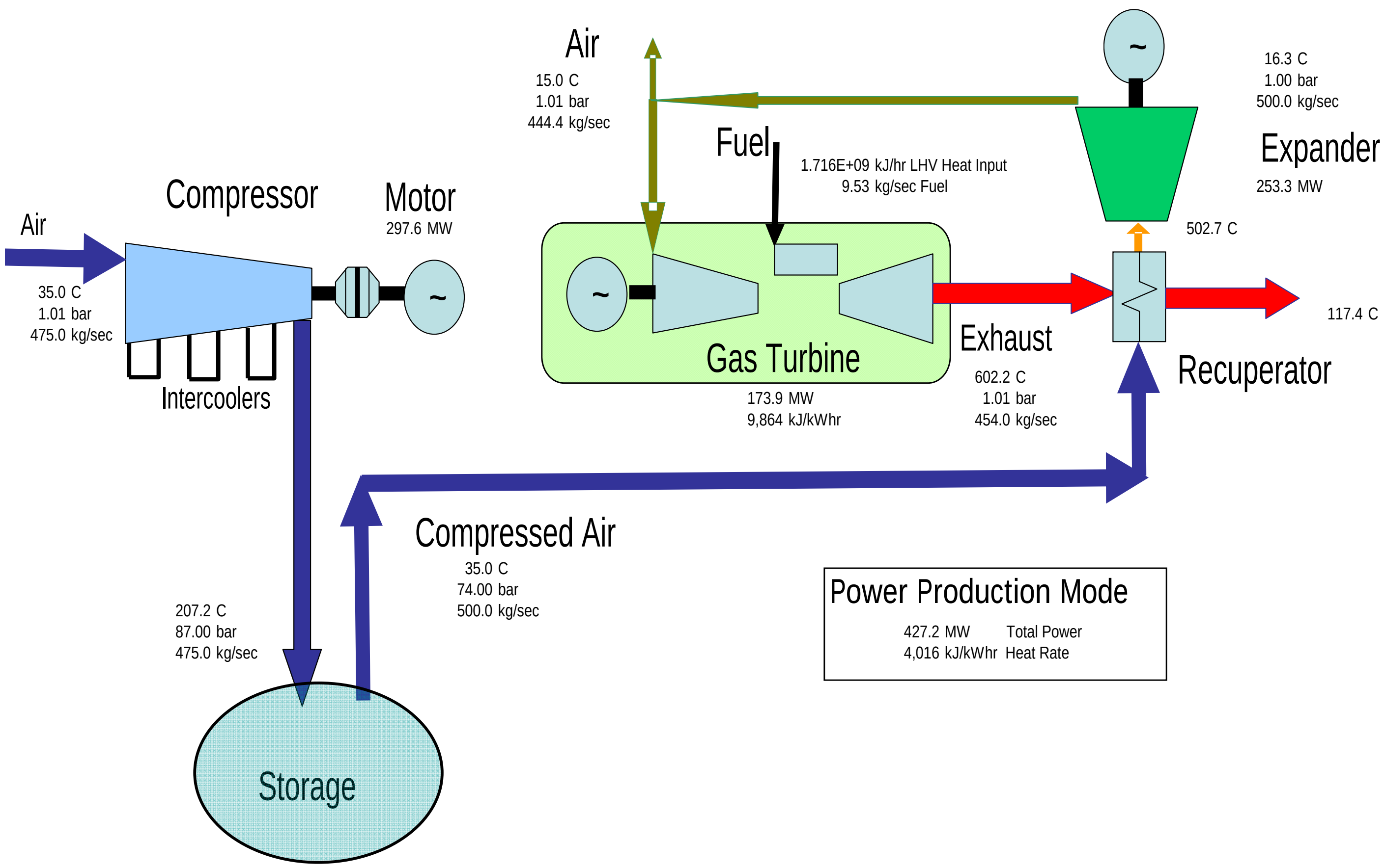


Figure 4.5: Schematic and Heat and Mass Balance for the CAES/Expander/Inlet Chilling Plant Option
Source: Electric Power Research Institute

The table below summarizes the major performance characteristics of CAES/Expander/Inlet Chilling design and a Combustion Turbine.

	CAES/Expander/Inlet Chilling Plant Option Based on GE7241-FA CT	GE7241-FA CT (at 95F)
CT power, MW	159.8	160
CAES power, MW	267.4	NA
Total power, MW	427.2	160
Total heat rate, Btu/kWh	3811	10,600
Off-peak compressor power, MW	297.6	NA

4.2.5. CAES/Expander Plant Option

The schematic of the CAES/Expander concept with major performance characteristics are presented on Figure 4.6. This concept practically has the same components as the CAES/Expander/Inlet Chilling concept with the following differences:

- The expander is not sized to meet the CT inlet flow requirements and therefore has some flexibility in its sizing
- The expander exhaust is not directed to the CT inlet.

The CAES power is the expander power in the upper right corner of the below figure.

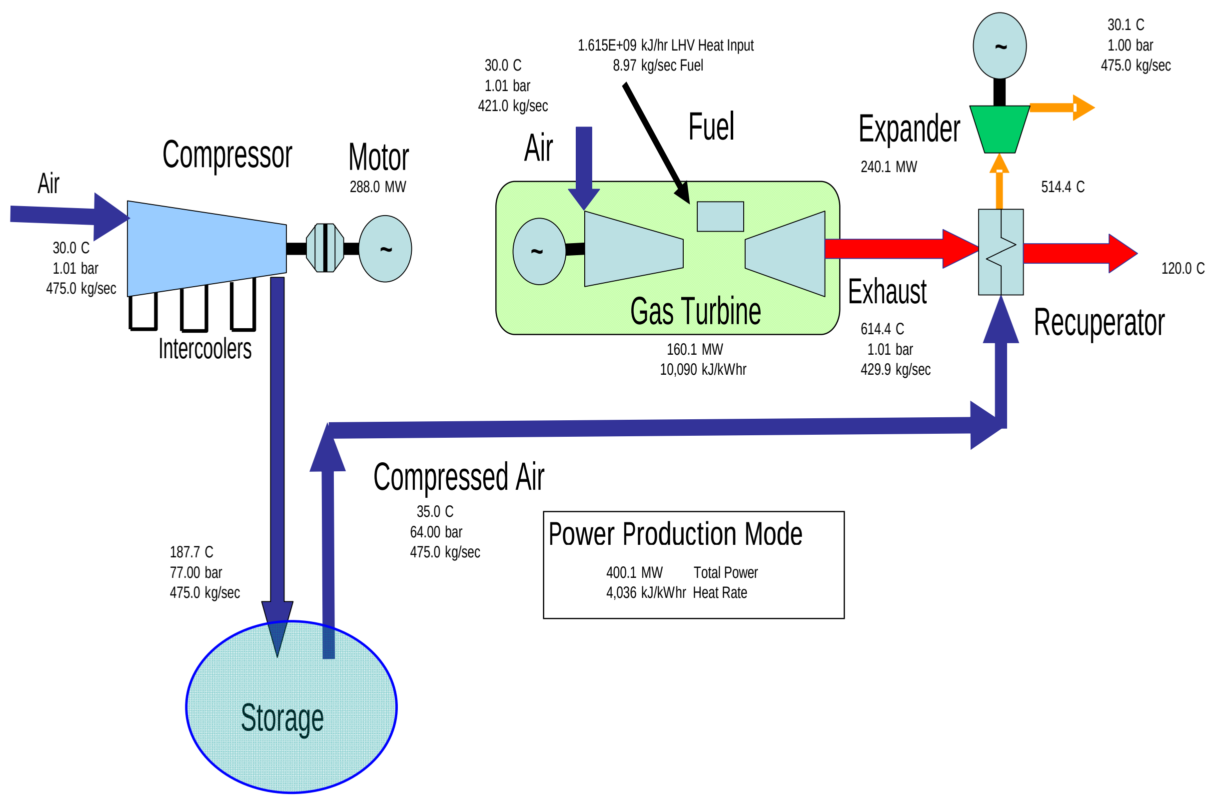


Figure 4.6: Schematic and Heat and Mass Balance for the CAES/Expander Plant Option
Source: Electric Power Research Institute

The table below summarizes the major performance characteristics of CAES/Expander design and a Combustion Turbine.

	CAES/Expander Plant Option Based on GE7241-FA CT	**GE7241-FA CT (at 95F)**
CT power, MW	159.8	160
CAES power, MW	240.2	NA
Total power, MW	400	160
Total heat rate, Btu/kWh	3826	10600
Off-peak compressor power, MW	288	NA

4.2.6. Adiabatic Concept

A relatively new type of CAES plant design option not based on a CT power block will now be described; namely, the Adiabatic CAES plant design option, which uses no fuel to generate power, once off-peak electricity is used by the compressors to store the air. The schematic of the Adiabatic CAES plant option, and its major performance characteristics are presented on Figure 4.7. The adiabatic plant option is based on a conceptual design and principles presented in the EPRI report "Thermal Energy Storage for Advanced Compressed Air Energy Storage Plants", developed under EPRI project AP-5844.

This CAES plant option has the following components:

- Off-peak electricity is used to power the LP and HP compressors, with one intercooler and one aftercooler optimized to generate hot discharge compressed air that is stored and later used during the peak power generation cycle
- A thermal energy storage system is used to store the compressed air heat in the form of heated thermal oil (or possibly a pebble bed of sensible heat rock media)
- Heat exchangers are used to transfer the heat from the compressor discharges to the thermal store, and from the thermal store
- HP and LP Expanders use stored and preheated compressed air for the CAES power generation cycle

The major advantage of this concept is that it does not require any fuel during its generation cycle.

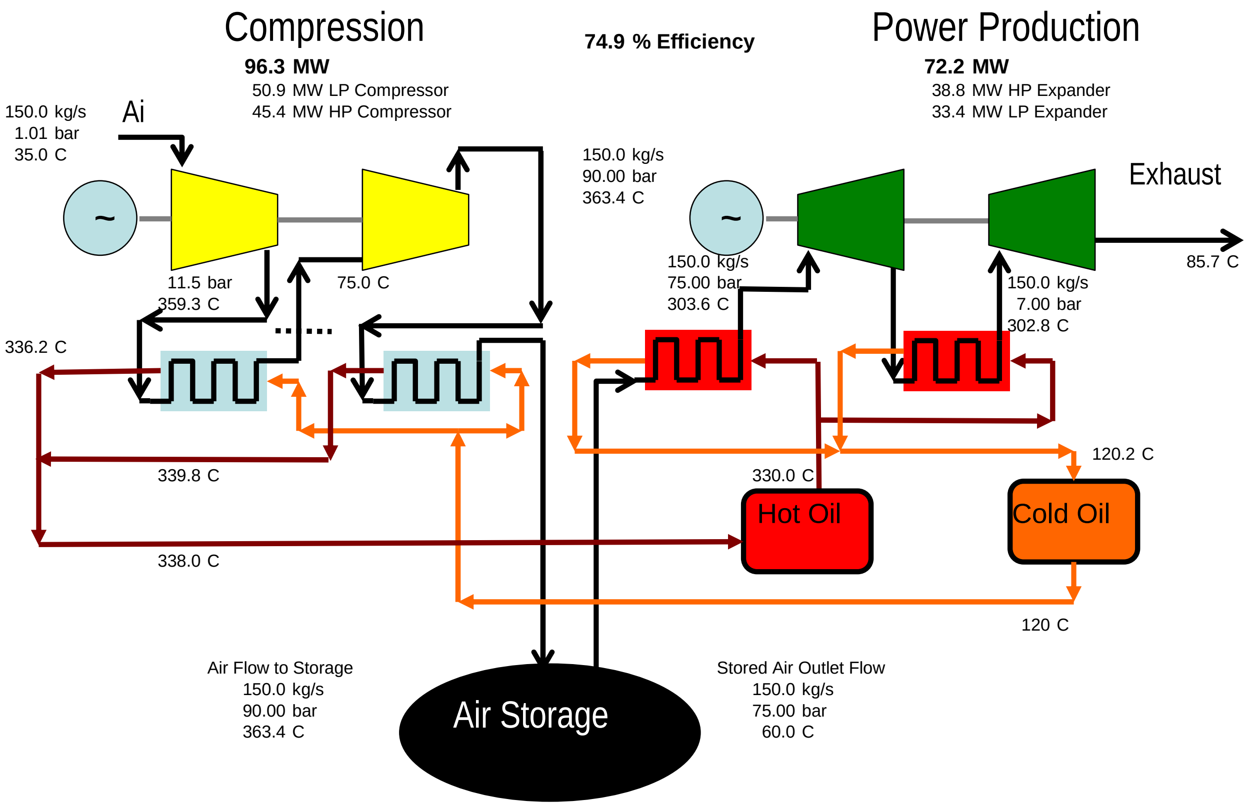


Figure 4.7: Schematic and Heat and Mass Balance for the CAES Adiabatic Plant Design Option
Source: Electric Power Research Institute

The table below summarizes the major performance characteristics of CAES Adiabatic plant option.

	CAES Adiabatic Concept
CAES Power, MW	72.2
Total Heat Rate, Btu/kWh	0
Off-peak Compressor Power, MW	96.3

4.3. Capital Cost Estimates

The capital costs for each of the CAES plant design options analyzed in this project were estimated in 2007 dollars, based on a parametric approach equally applied to all designs. As guidance, the actual cost breakdown for the AEC's CAES plant was used, including the costs for the underground storage system and specific costs ($/kW) and proposals for similar turbomachinery for current CAES plant projects that are under development.

Capital cost estimates for each CAES plant design option were performed in three steps:

- Parametric estimates of the equipment costs were developed, based on specific parameters that resulted from the design investigated and its heat and mass balances.
- Estimates were developed of the material and labor costs for plant installation.
- Estimates were developed for the underground storage system by proportioning the underground storage costs of the AEC's CAES plant to the design option analyzed.

For equipment pricing, the focus was on projects with comparable equipment parameters and scope of supply. The equipment and material costs were scaled to match the size and capacity for each CAES plant design option investigated. Due to the nature of the comparative capital cost estimates, certain site specific optional equipment that could be equally applied to all designs (such as selective catalytic reduction equipment, buildings, and bridge cranes) were not specifically estimated and were accounted for by generic multipliers. Labor costs for engineering, installation, startup and other services were estimated, based on median site.

The cost estimates of the underground store for all the CAES plant design options analyzed were based on the specific geological formation of the AEC 110 MW CAES plant; and the air storage costs were prorated for each design investigated based on the air flow rates needed by that design.

In reality, it is known that actual plant costs will vary based on such items as the geographic location of the CAES plant, currency valuations, and competitive market conditions. For this study the costs are maintained consistent with the technology, and the overall costs provide sufficient information for a relative comparison of the selected CAES plant designs.

4.4. Capital Cost Estimate for Equipment

Capital costs for the following major components were estimated for each design option:

- The air compressors
- Turboexpander trains for the conventional and adiabatic designs
- Combustion turbine for each CAES plant design
- HP and LP turbo expanders
- Heat recovery recuperator
- Electric generators
- Associated balance-of-plant equipment
- Underground storage

The following is a brief description of the parametric approach applied to various plant components.

Air Compressor Package: The air compressor costs are based on actual quotations (by Ingersoll Rand and Cooper-Turbocompressor) and the compressor costs for the AEC's CAES project, which were prorated based on the air flow and discharge pressure for each design investigated. A specific cost of approximately 30 $/kg/h at 80 bar was used. The air compressor system configuration is assumed to be skid mounted for outdoor installation, with standard motor and control systems provided by the vendor. The air compressor is a standard centrifugal compressor design, with split casing and heavy duty stainless steel impellers. The compressor lube oil system consists of an integral lube oil system and a water-cooled heat rejection system.

Turboexpander Package: The turboexpander costs are based on a range of specific costs between $150/kW and $170/kW that were applied to the various CAES plant designs analyzed, based on experience. The turboexpander configuration is assumed to be skid mounted for outdoor installation, with a standard control system supplied by the vendor. The major components include:

- Turbine and enclosure
- Turbine electrical package/mechanical package
- Turbine generator starting/control and excitation skid
- Generator and generator transformer

Heat Recovery Unit: For each CAES plant design investigated, heat recovery units are priced based on calculated heat transfer surface area. Based on data obtained from experts involved in the recuperator design for the AEC CAES projects, ESPC used the unit rate of 15 $/sq.ft. for a 20 MJ/s heat exchanger at 40 bars rated pressure. The total cost is adjusted for size and pressure rating for each of the CAES plant design options investigated. The heat recovery unit is an extended surface type air-to-air heat exchanger designed to be installed in the exhaust gas duct of the plant. The unit has an all welded pressure part construction with tubes in a top-supported unit to provide for unrestricted downward thermal expansion. The unit will be shop fabricated and have heat transfer modules installed inside the shop fabricated casing sections, for one piece erection onto foundations in the field. A similar design approach is used for stand-alone air-to-air heat-exchangers.

Gas Turbine Package: For the CAES plant design options using the GE7241-FA combustion turbine power block, a common comparative capital cost analysis approach was used. The cost of the CT equipment package from the factory, including all auxiliaries, is estimated at approximately 220 $/kW based on past quotations and published data that does not include installation costs. The CT configuration will be skid mounted for outdoor installation, with standard control systems provided by the vendor. The major CT components include:

- Combustion turbine and enclosure
- Combustion turbine electrical package and mechanical package
- Combustion turbine starting and excitation skid

- Fuel gas metering equipment
- Generators and generator step-up transformers

Air Injection System: The CAES-AI plant options include the Air Injection (AI) power augmentation technology. The AI technology is currently an ESPC proprietary technology that has been validated on a GE 7241-FA Combustion Turbine at the US Broad River power plant. The technology is based on the injection of externally compressed air into the combustion turbine at any point upstream of combustors.

Compressed Air Storage: As it was mentioned above, the cost estimates for the underground storage for all the CAES plant design options were based on the specific geological formation used by the AEC 110 MW CAES plant; and, the air storage costs were prorated for each CAES plant design option investigated. The major data used in these analyses were:

- AEC cavern costs were approximately $7M
- 40% of the costs were allocated for the airshaft
- 60% of the costs were allocated to solution mining, to create the air volume required for 2600 MWh's of continuous CAES plant power output

4.5. Equipment Installation and Overall Construction Costs

Installation prices vary considerably depending on site location, labor unions, and local labor rates. In most cases special infrastructure "adders" are applied to the plant installation costs; e.g., for such items as the need for access roads, power transmission requirements, fuel gas pipeline extensions, training centers, and repair facilities, all of which can significantly increase the overall CAES plant cost. The pricing shown below are for a standard single fueled plant. Site and plant layout, installation, special subsoil design conditions, and "adders" can increase the price of the completed plant by as much as 80%. However, it can be reasonably assumed that such costs will affect all the CAES design options being considered on an equal prorated basis. In any case, it is prudent to evaluate possible site related costs which can make one technology design option significantly better or inferior as compared to another plant design option.

Balance of Plant Equipment and Services: Standard auxiliary systems and controls, required to operate a plant design configuration, are included in the cost estimates. The estimates also include services for plant engineering, construction management, and startup. The major items excluded are: plant licensing costs, permit costs, off-site roads, fuel pipeline, substation, fuel gas compressor and conditioning equipment, backup fuel, special tools, operational spares, consumables, and black start generator sets. Such items are site or owner specific optional equipment and are not part of a standard turnkey scope of equipment supply.

The cost estimates for the CAES plant design options investigated include the following balance-of-plant systems and services:

- Plant engineering and design

- Equipment foundations and site civil works
- Piping systems, supports and insulation
- Chemical feed handling equipment
- Water treatment/waste water systems
- Motor control centers
- Plant control and monitoring equipment
- Electrical and control cabling
- Construction management and startup

A summary of the capital cost estimates for each CAES plant design option analyzed in this report is presented in Table 4.2.

Table 4.2: Summary Cost Estimates of Second Generation CAES Plant Design Options. The combustion turbine used to produce the data in Columns 3 through 7 was a GE Frame 7A CT. The costs are only to be viewed on a relative basis and not on an "absolute" cost basis. They are for a 10-hour underground salt-based air storage system, or for a 2-hour above-ground air storage system.

Study Case / Cost US$ x1000,s	CAES Conven-tional	CAES-AI no Expander	CAES-AI w. HP Expander	CAES-AI w. HP & LP Expander	CAES W. Expander	CAES w. Expander & Inlet Chilling	Adiabatic
Major Equipment Cost:							
Combustion Turbine	NA	38,000	38,000	38,000	38,000	38,000	NA
Air Compressor	9,000	3,200	3,400	23,000	21,000	22,000	9,000
Heat Exchangers	3,500	1,700	2,400	14,000	13,000	14,000	10,500
HP Expander	6,400	NA	2,400	16,000	35,000	35,000	8,000
LP Expander	14,900	NA	NA	24,000	NA	NA	7,000
Electrical & Controls	4,700	4,200	4,300	7,500	6,500	6,500	4,200
Total Major Equipment	38,500	47,100	50,500	122,500	113,500	115,500	38,700
Construction Cost:							
Materials	7,000	1,900	2,000	9,200	8,500	8,600	3,100
Labor	16,000	14,000	14,600	39,300	36,000	36,400	14,700
CAES Storage	8,000	3,000	3,000	19,000	18,000	18,000	6,000
Indirect Costs	10,500	10,700	11,400	29,000	26,800	27,300	9,600
Estimated Total Cost	**80,000**	**76,700**	**81,500**	**219,000**	**202,800**	**205,800**	**72,100**
Specific Capital Cost $/kW	**727**	**397**	**403**	**506**	**507**	**482**	**1,001**
Total Installed MW	**110**	**193**	**202**	**433**	**400**	**427**	**72**

Source: Electric Power Research Institute

4.6. Above-Ground Storage Air Storage Systems for CAES

EPRI and ESPC conducted extensive feasibility studies concentrated on the development of man-made above ground storage systems. These efforts were primarily driven by two issues:

- To eliminate any geological restrictions for the location of a CAES plant
- To accommodate specific applications of low capacity CAES plants for renewable resources (e.g., wind power plants), distributed power generations or other load management/frequency regulation plants

Presented below is the analysis and results (based on past and present EPRI work) on the above ground storage alternatives that can be used for CAES, including air storage using buried pressure vessels, concrete ring type pipes or piping used to transport natural gas. The studies identified that air stores using buried piping of 2-3Ft diameter, located in specifically designed trenches (with proper isolation and cathodic protection) with a maximum pressure of approximately 1500 psia is the most cost effective alternative (see EPRI's report: Transient Analysis of Hybrid Plants, WO 4481-02).

The volume and costs of the above ground storage for each CAES plant design option could be relatively estimated based on established specific costs of approximately $50/kWh and applied to each design option analyzed based on its MW capacity and the air storage requirements.

5.0 Natural Gas Pipelines and Transmission Lines in California Provide Energy Portals for Use by Compressed Air Energy Storage Plants

Because of California's economic and demographic significance, it has a number of existing gas pipe lines and many in construction. Interstate gas pipeline companies obtain great economic value from their underground gas storage facilities, which perform a needed gas delivery load management function by enabling pipeline companies to store and later use large volumes of gas during the year as the prices change on a predictable seasonal basis (i.e., gas prices are lower in summer than in winter). Also, local gas distributors depend on gas storage facilities to meet quick response gas demands as their customers change load unpredictably, which then impact the gas demands on interstate gas pipeline companies.

In the next 5 years, the three States that will see a dramatic increase in pipeline construction are California, Arizona, and Oregon. Underground gas storage projects also have increased, with 73 projects to be completed in 2008. Of these projects, 26 are new facilities; whereas, the other 47 are additions to already existent gas storage facilities. These projects, when completed, will offer a daily deliverability rate of 17 BCF and can add almost 346 BCF of capacity to the existing natural gas system in the US.

Presented below are California maps for electric transmission lines, natural gas transmission pipelines and underground geologic formations suitable for CAES. Of course, the "best" sites are those that have all three of these infrastructures close to them.

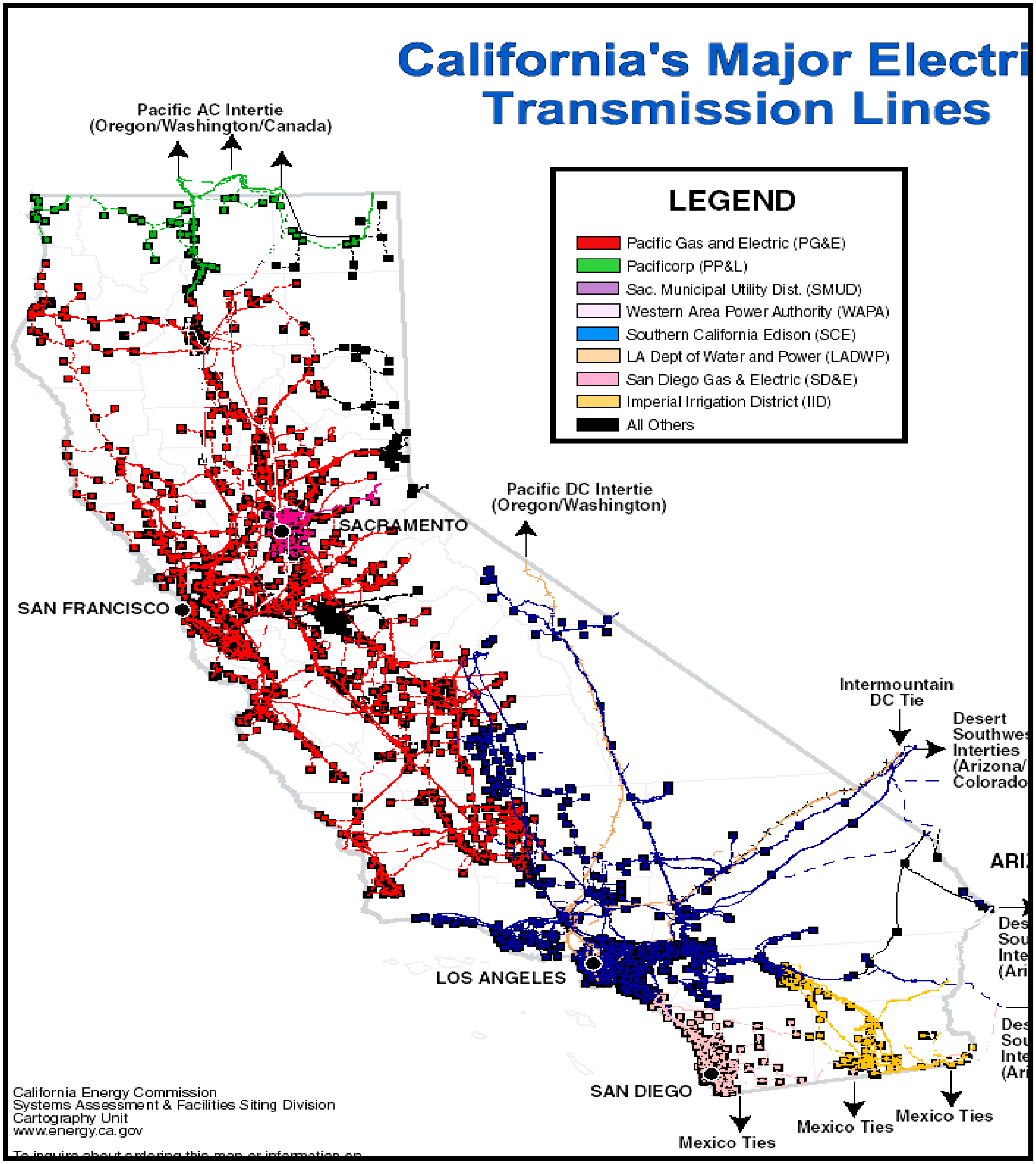


Figure 5.1: Major High Voltage Electric Transmission Lines in California
Source: Electric Power Research Institute

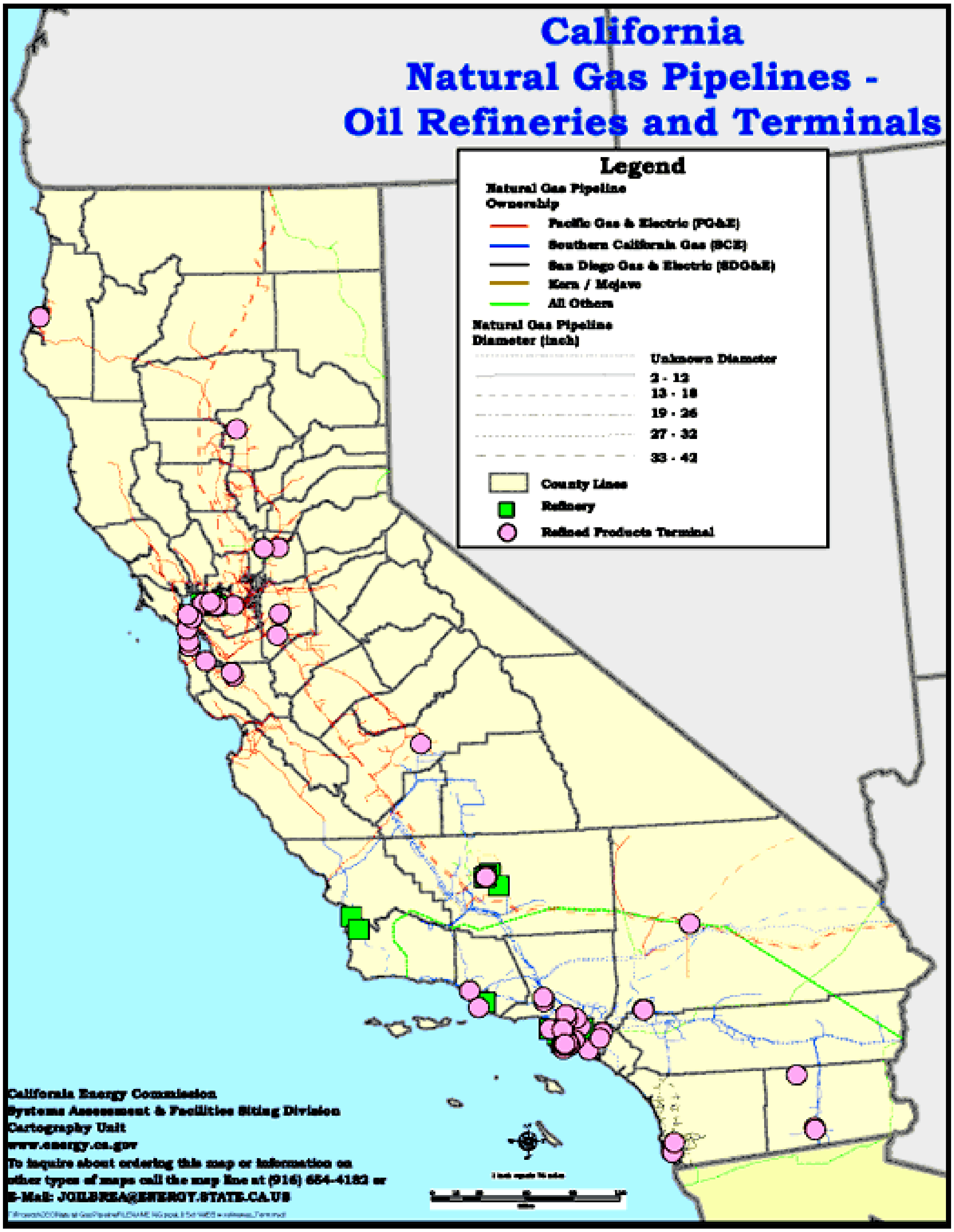


Figure 5.2: Natural Gas Pipelines, Oil Refineries, and Terminals in California
Source: Electric Power Research Institute

Figure 5.3: Existing and Proposed Natural Gas Pipelines in California (Natural Gas Storage Facilities are also shown)
Source: Electric Power Research Institute

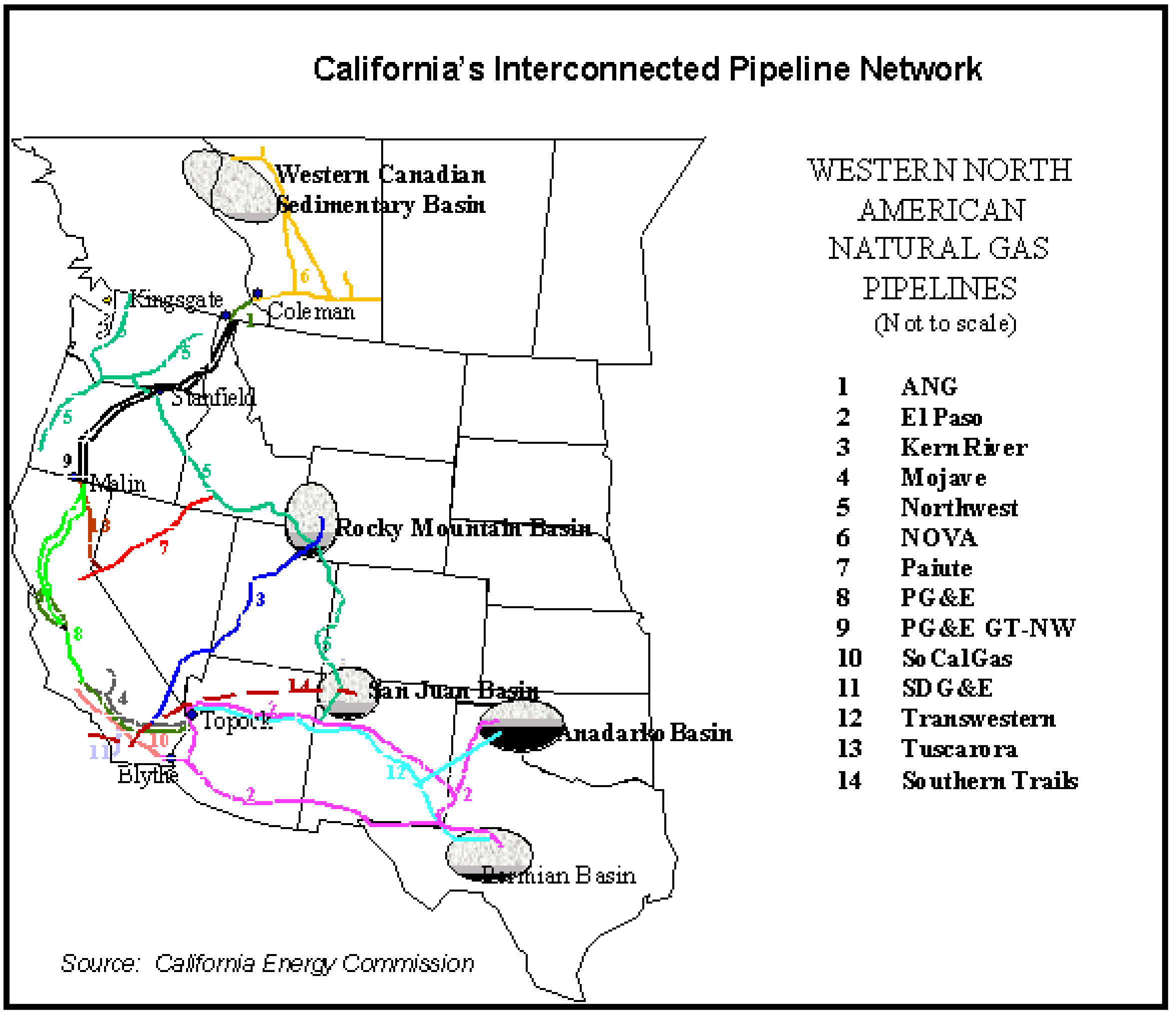


Figure 5.4: State Interconnected Natural Gas Pipeline Network in California
Source: Electric Power Research Institute

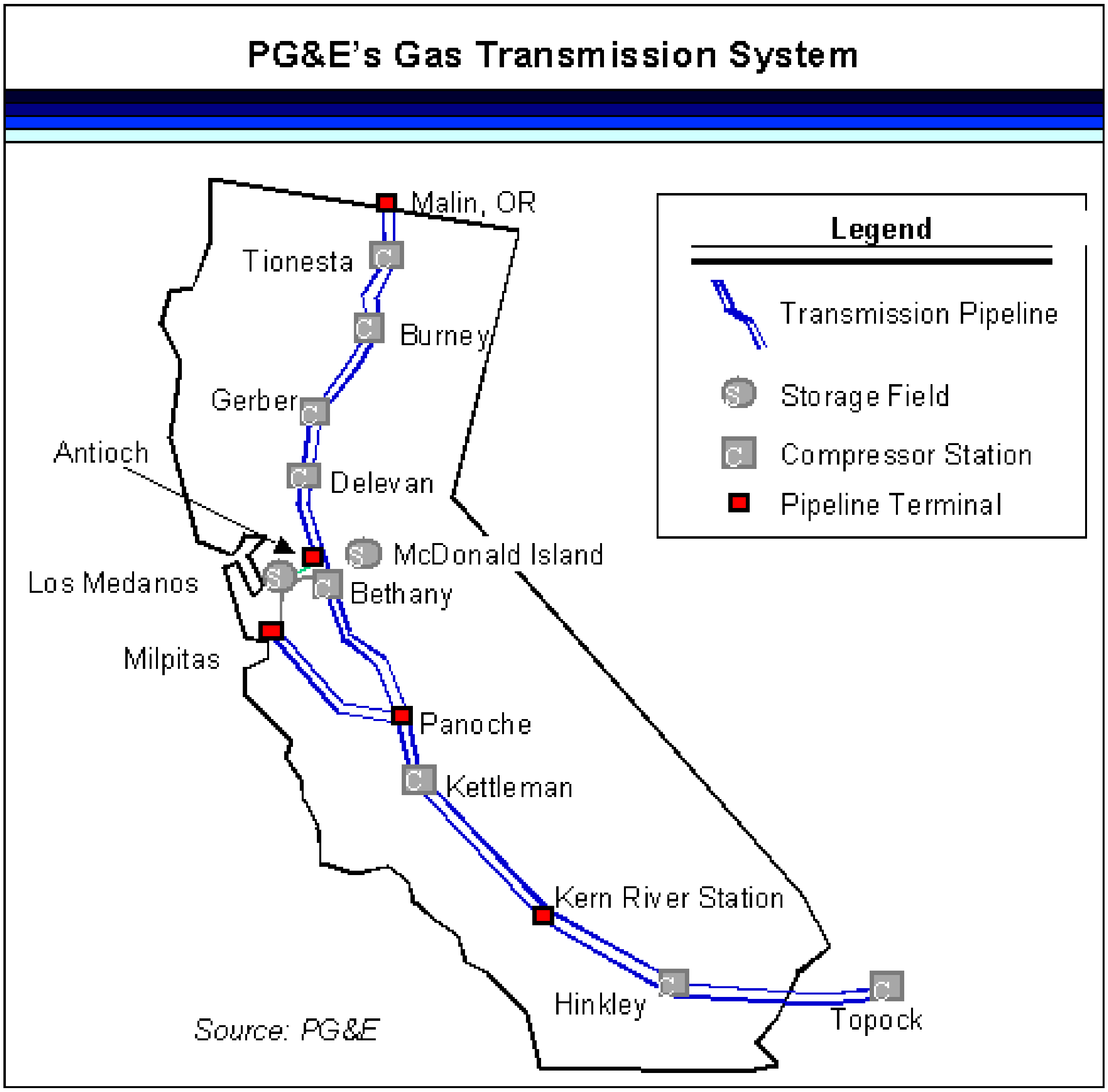


Figure 5.5: PG&E Gas Transmission System in California
Source: Electric Power Research Institute

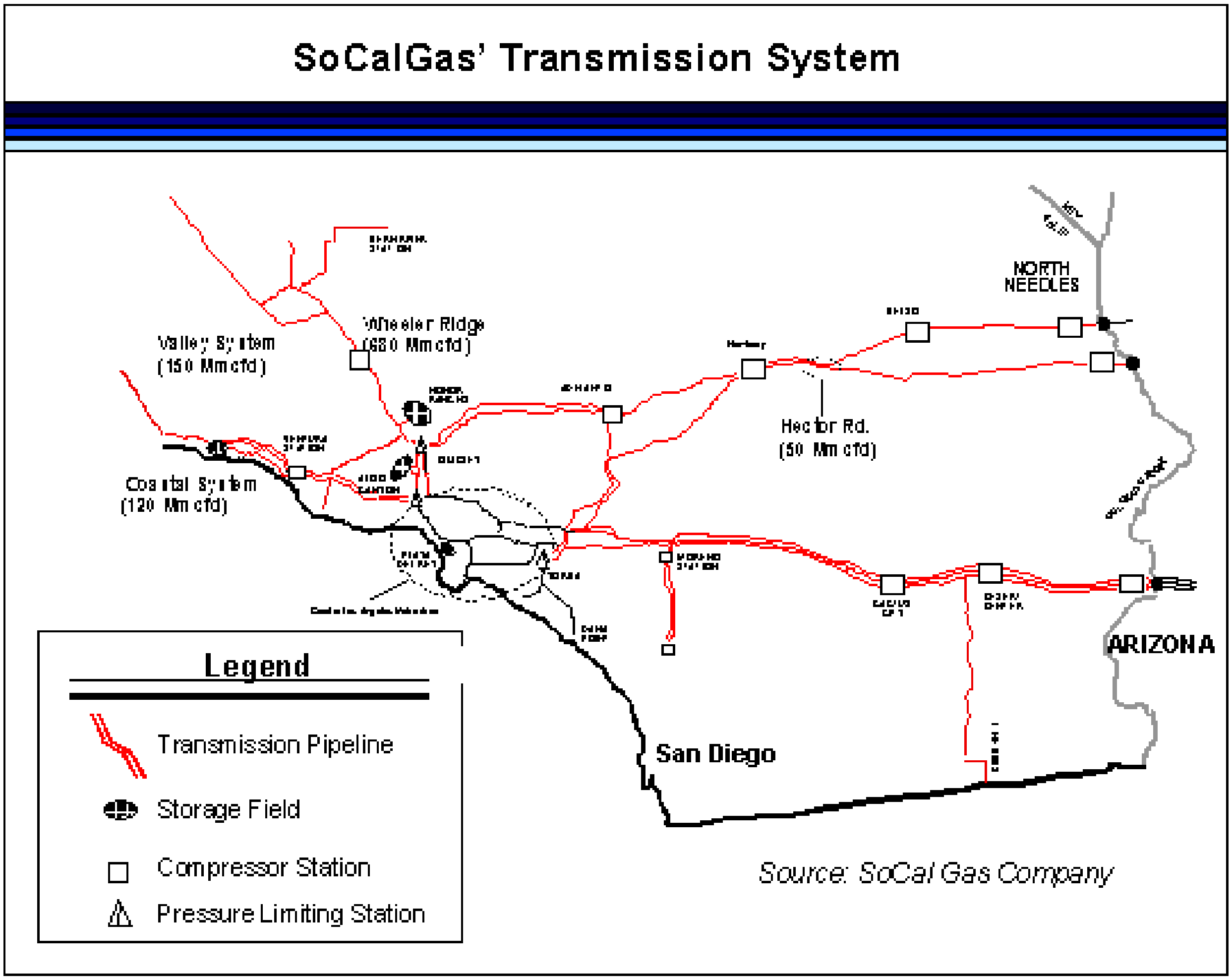


Figure 5.6: SoCalGas' Natural Gas Pipeline Transmission System
Source: Electric Power Research Institute

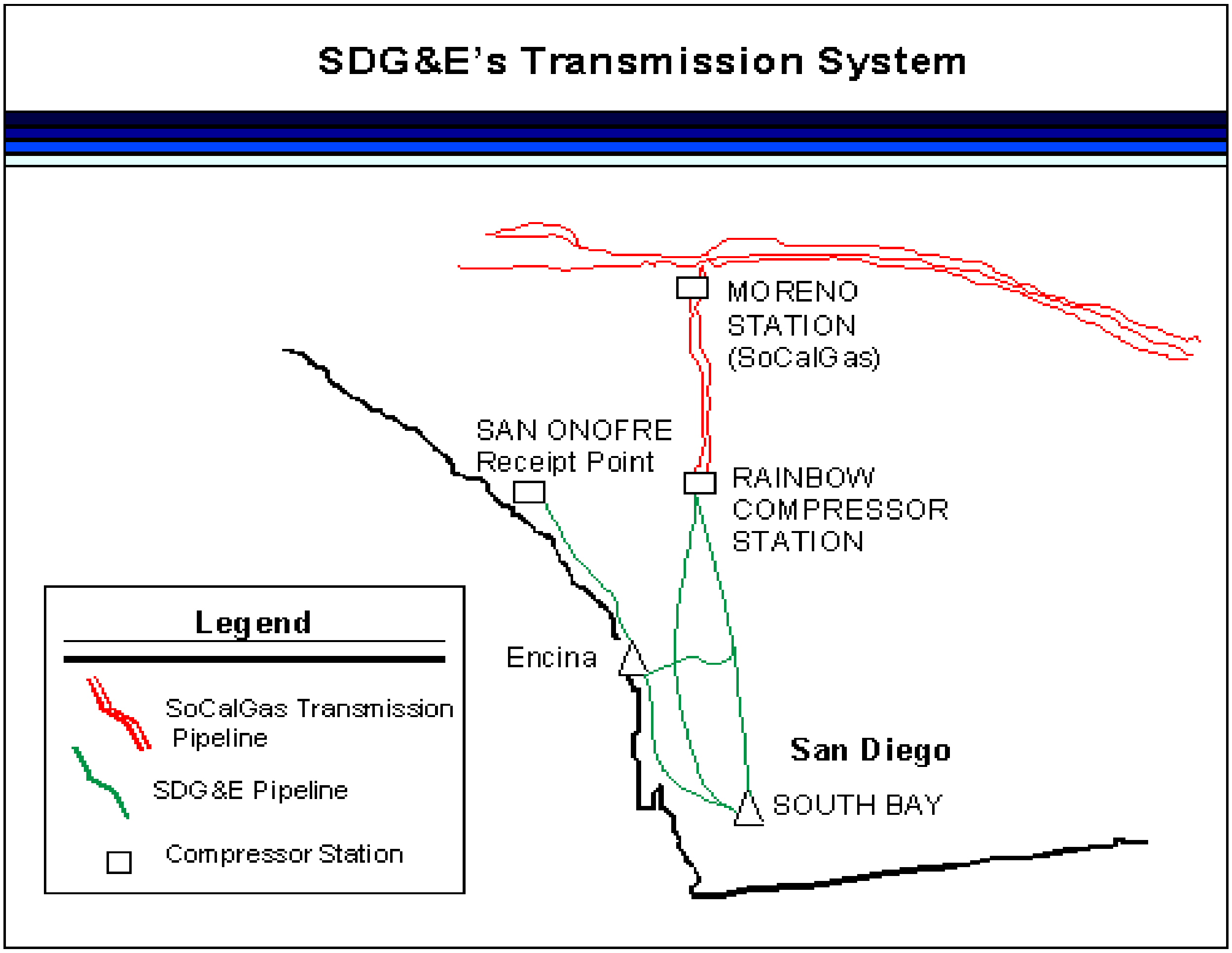


Figure 5.7: San Diego Gas & Electric's Natural Gas Pipeline Transmission System
Source: Electric Power Research Institute

6.0 Conclusions and R&D Opportunities to Deploy CAES Plants in California

The major R&D efforts associated with CAES in California should be focused on verifying underground air storage formations, and conduct field tests to cycle air daily (following a CAES duty cycle) in at least two types of air reservoirs (namely, one for a depleted gas field and one for a depleted oil field). First, core samples should be acquired and investigated with respect to identifying any potential issues associated with the oxygen geochemistry in these formations. This can be done using standard autoclave systems on core samples taken from the depleted gas/oil sites, which can be obtained from the local State Geologic Survey, or if necessary, by drilling into the underground formation with a small bore drilling rig to obtain "clean" core samples for the needed geochemical investigations.

Analysis of specific characteristics for the new CAES plant design options, as well as for the no-fuel adiabatic CAES design option, was driven by a desire to lower plant costs and to simplify the overall plant equipment layout and connections, and use standard components and systems wherever possible. Even so, there are a number of R&D efforts required to ensure reliable and cost effective CAES plants for implementation in California, where there is a growing renewable portion in the generation mix for State.

Most, if not all of the R&D issues associated with the new CAES plant design options could be effectively addressed by demonstration projects with well thought-out test procedures to apply the demonstration projects results to a variety of CAES plant design options, differentiated by size and equipment module additions.

These demonstration projects could easily utilize existing old small capacity combustion turbines to reduce the capital costs and plant capacities of the demonstration plants. These projects would allow integrating various CAES plant configurations with the above ground storage systems as well, with about 2 to 3 hours storage. Special hybrid designs could be provided to address various concepts including the adiabatic design, and to apply results of the demonstration project to a variety of applications.

The major characteristics of the new CAES plant design options show that they are all based on a combustion turbine, and therefore a demonstration project could be based on any available existing combustion turbine a California utility is not using much, or is willing to contribute it to a CAES demonstration project. Also, the amount of air in the exhaust stream of this combustion turbine used in the demonstration project can be much smaller than all the exhaust air available, since all the demonstration project has to do is provide a proof of principle to the thermodynamic and performance characteristics expected. For example, the demonstration plant need only by 1 MW to 5MW if it only uses a portion of the exhaust air for heating the stored air; or, the demonstration plant could use all the exhaust air flow and produce 20 MW's to 100 MW's of output power, depending on the size of the combustion turbine the California utility provides for the demonstration project.

The above R&D suggestions and others are summarized below, in recommended priority order:

- Work with California utilities to identify potential CAES sites within their regions and verify underground geologic conditions applicable to CAES (e.g., perform core sample chemical analyses, and porosity, permeability and storage pressure and capacity investigations).
- Using a new or used CT from a California host utility, build and test a CAES-CT demonstration plant. Depending on the amount of air flow directed from the CT exhaust, the CAES-CT plant could produce 5 MW's to 100 MW's of plant output.
- Perform thermodynamic trade-off studies to choose a preferred CAES-CT plant design and determine the plant parameters appropriate to California geologic site conditions and California off-peak/on-peak renewable energy economic conditions.
- Perform air storage cyclic field tests at one or more California CAES sites and test CAES-CT combustor performance, using different air residence times in the storage reservoir, which will determine if chemical reactions in the air store could impact the plant's performance.
- Design and build a prototype above ground air store system, and perform field tests to determine corrosion or cyclic fatigue issues.
- Develop a preferred no-fuel CAES plant design (i.e., the adiabatic CAES plant design option) and perform lab/field tests to determine the preferred thermal store materials that are best suited for California conditions.
- Analyze CAES plant design options based on using alternative fuels (e.g., biofuels, and hydrogen).
- Analyze adding a synchronous condenser feature to appropriate CAES-CT plant design options, since +/- VAR injection is needed in California as more wind or other renewable generation plants are put into service (e.g., "excite" the compressor motor, the CT generator, and the expander generator to enable them to be used as synchronous condensers).

7.0 Glossary

AI	Air Injection
AEC	Alabama Electric Cooperative
BCF or bcf	Billion Cubic Feet
BOP	Balance of Plant
CEC	California Energy Commission
CAES	Compressed Air Energy Storage
CF or cf	Cubic Feet
CT	Combustion Turbine
EPRI	Electric Power Research Institute
Gt	Gega Ton (1000 Mega Ton, 1 Billion Ton)
HP	High Pressure
HRR	Heat Recovery Recuperator
IPP	Independent Power Producer
LP	Low Pressure
MM	Million (from Roman Numerals)
Mt	Mega Ton (Million Ton)
MW	Mega Watt (Million Watt)
NA	Not Applicable
PG&E	Pacific Gas and Electric
PB-ESS	Parsons Brinckerhoff (PB) Energy Storage Services (ESS)
PV	Photo Voltaic
R&D	Research and Development
SDG&E	San Diego Gas and Electric
SoCalGas	Southern California Gas Company

8.0 Bibliography

1. 2005 California, Division of Oil, Gas and Geothermal Resources (DOGGR) publication of (active and abandoned) *Oil and Gas Field Production and Reserves.*

This is an annual report of all oil and gas production fields in California (2005 was the last complete year published). It lists each field and the reservoirs within the field. The data includes status (active or abandoned), classification (oil or gas), number of wells, location, reserves estimate and the total oil, gas and water production.

2. *Selection, Evaluation and Development of Porous-Media Reservoirs for Compressed-Air Energy Storage,* A research project (TR-104269) prepared for EPRI by Cascadia Exploration Corporation, Palo Alto, California, 1994

This report is an excellent source of information for the evaluation, design and development of a compressed air storage facility once a site location has been selected.

3. *Inventory of Underground Energy Storage Sites in California*, Prepared by Melissa Ann Jones, Systems Integration and Evaluation Office, Assessment Division, California Energy Commission, October, 1978

This report is a survey of Gas Fields, Aquifers, Oil Fields, Hard Rock Caverns, Caves and Mines that could be considered for compressed air storage.

4. *Feasibility of Compressed Air Energy Storage as a Peak Shaving Technique in California (Consultant Report)*, 2 Volumes, Prepared by Acres American Incorporated for California Energy Commission in cooperation with the US Department of Energy, September, 1978

This report is similar to the report prepared for EPRI by Cascadia Exploration in 1994, plus it contains design criteria for compressed air storage development in porous media and hard rock caverns.

5. *Compressed Air Storage for Electric Power Generation*, Katz, Donald L. and Lady, Edward R., Ulrich's Books, Inc. Ann Arbor, MI, 1976

This book is another excellent source of information on the technical design of compressed air storage site evaluation, selection and development.

6. *Geotechnic Survey to Identify Feasible Sites for Operation of a Compressed Air Energy Storage Electric generation Station*, Study for Sacramento Municipal Utility District (SMUD), Sacramento, CA, Two volumes, Fenix and Scisson, Inc., Tulsa OK, with Gibbs & Hill, Inc., New York, March, 1986

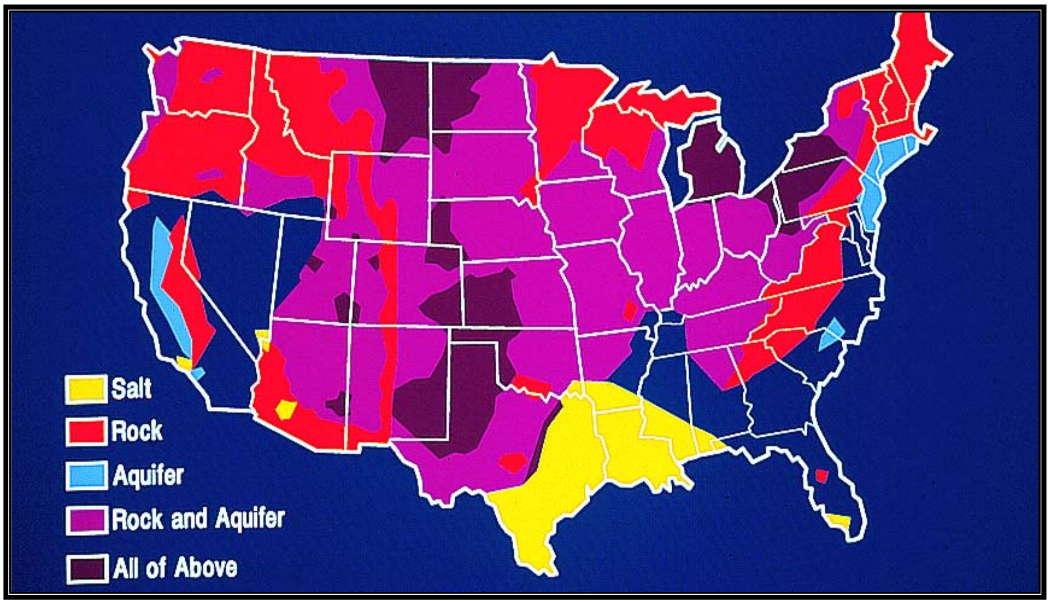
This report identified four (4) potential sites for CAES for electric generation, three (3) gas fields and one mined cavern site (Volume 1), and presents a general evaluation and design criteria for each of the selected sites (Volume 2). Fenix and Scisson is now PB ESS in Houston, TX.

Appendix A:

CAES Plant Siting Potential in the United States

For reference purposes, the map below shows CAES siting opportunities across the US. This map was put together by EPRI based on inputs from each of the lower 48 US Geologic Survey State offices.

Geologic Formations Potentially Suitable for CAES Plants That Use Underground Storage



Appendix B:

Geological Maps of California Showing Potential Sites for CAES Plants, Based on Existing Underground Fluid Reservoirs

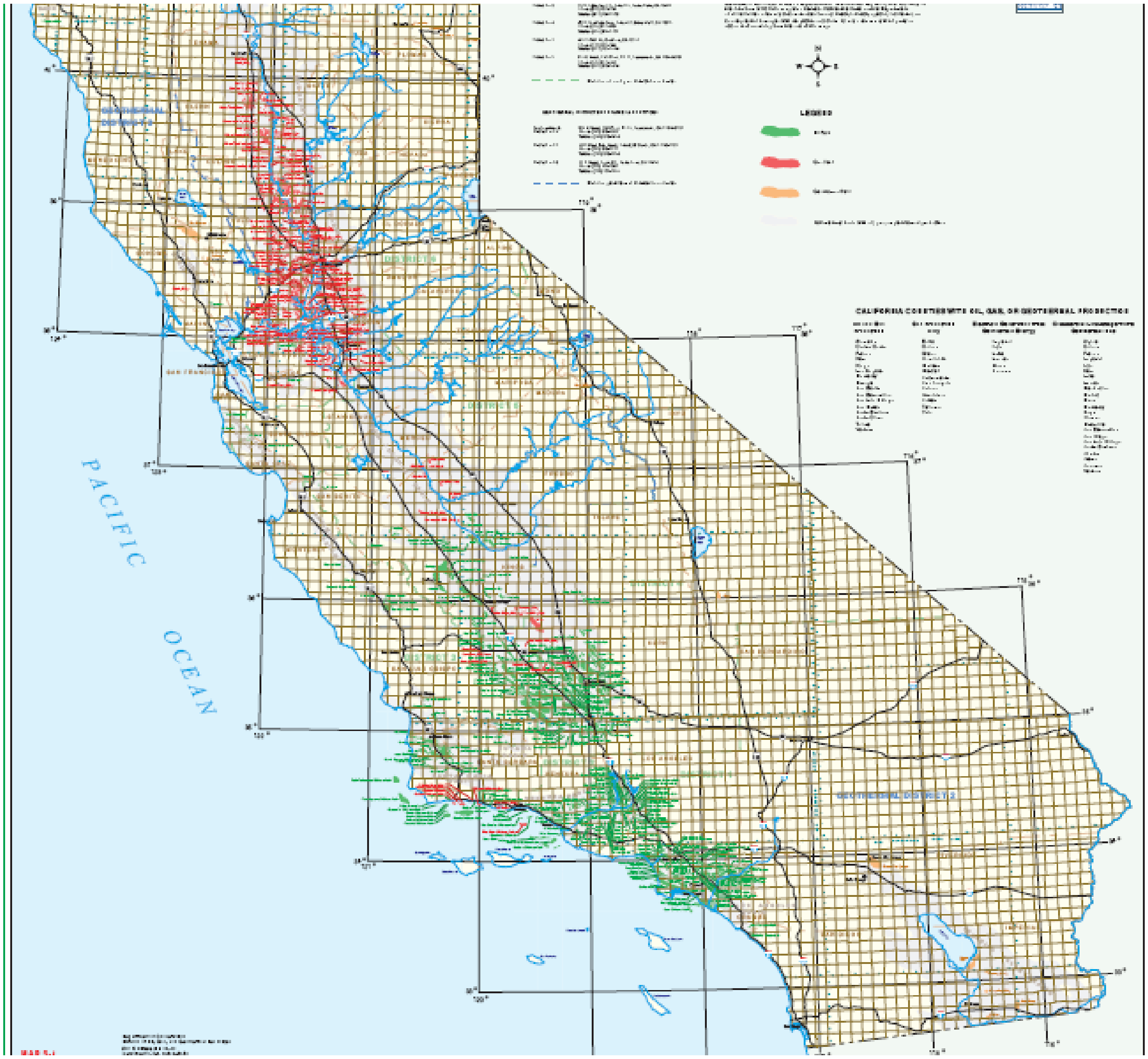


FIGURE B.1: OIL, GAS, AND GEOTHERMAL FIELDS IN CALIFORNIA

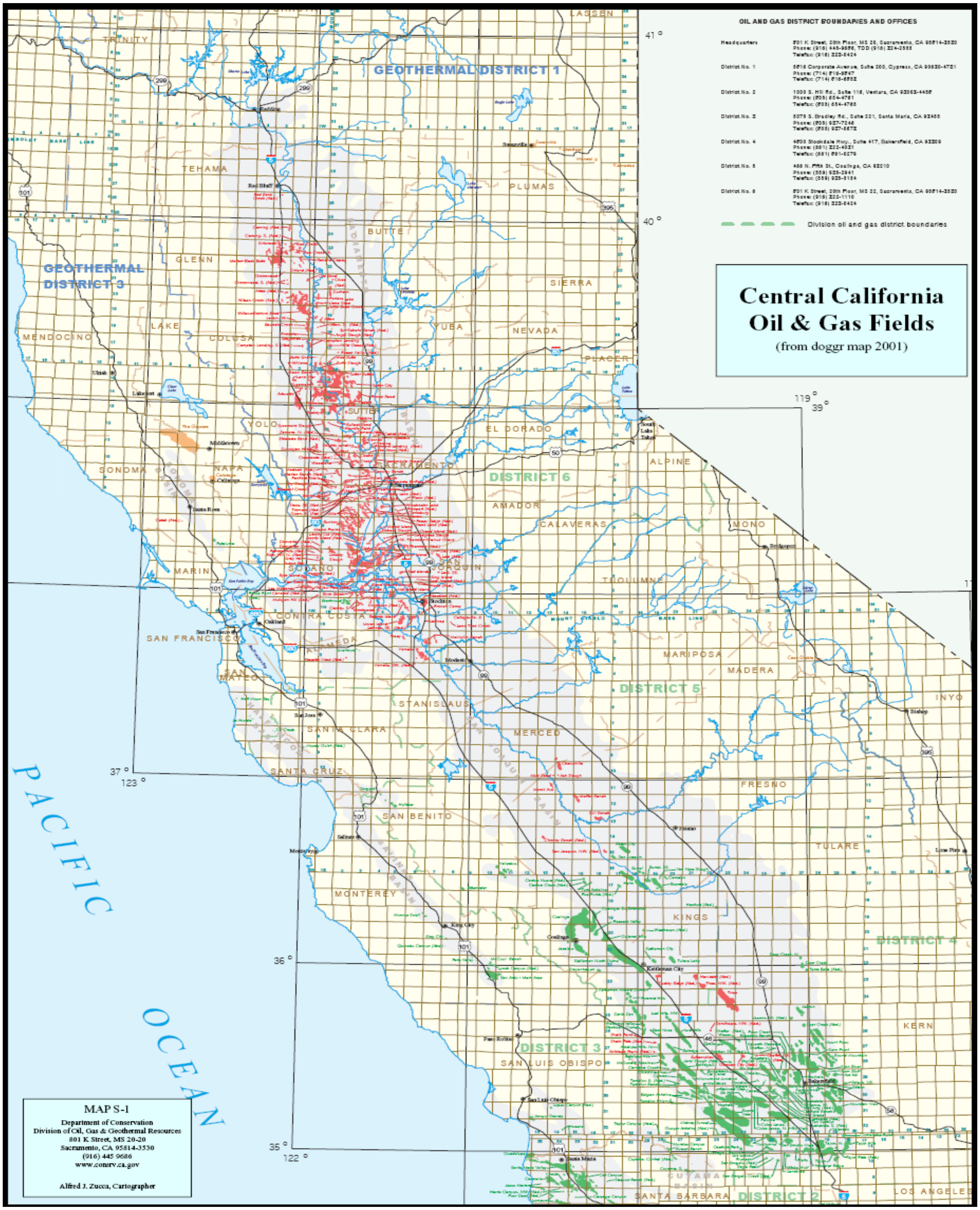


FIGURE B.2: CENTRAL CALIFORNIA OIL & GAS FIELDS

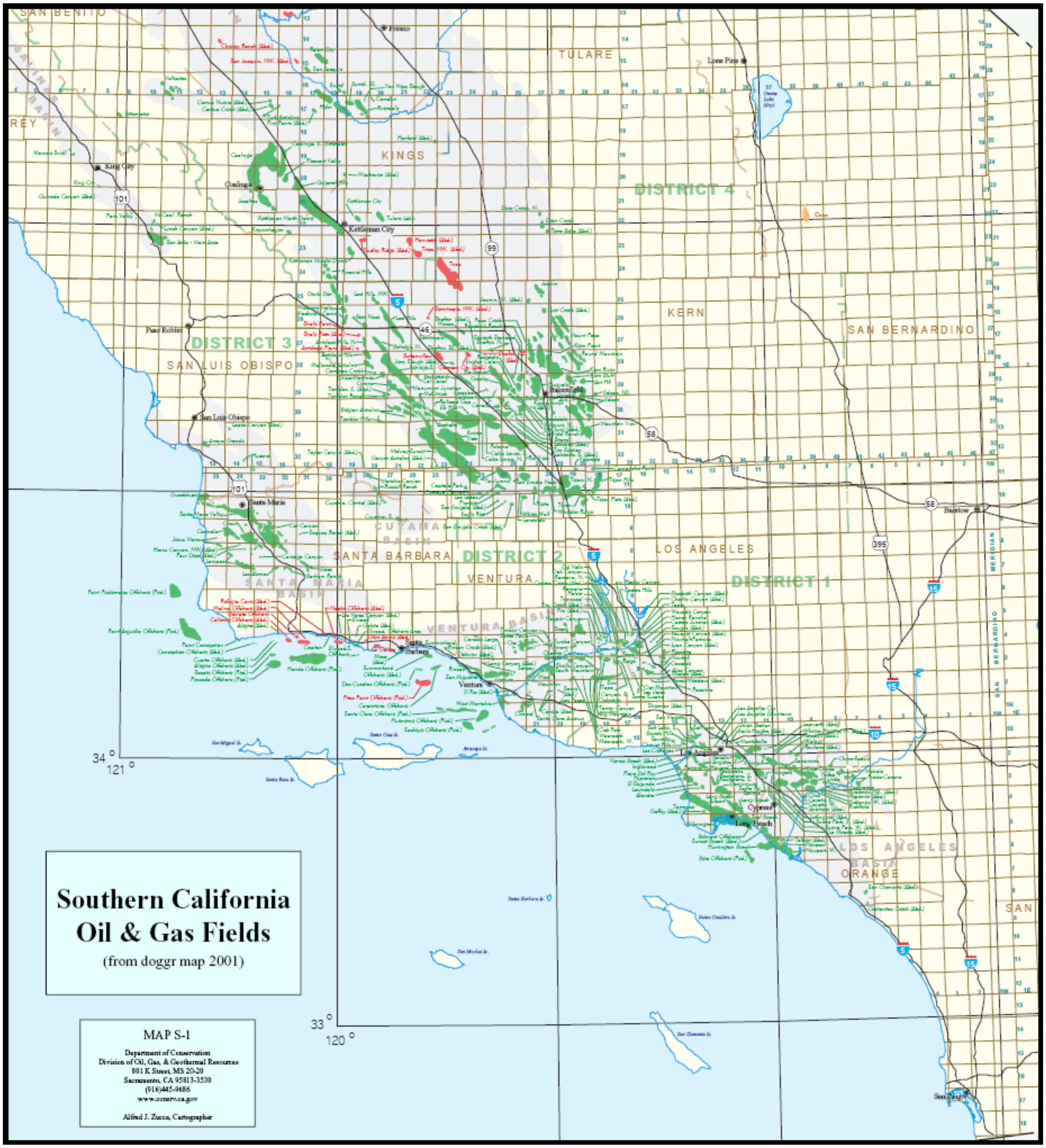


FIGURE B.3: SOUTHERN CALIFORNIA OIL & GAS FIELDS